

INVESTIGATION OF DISCONTINUITY IN PRECIPITATION MEASUREMENTS  
ACROSS CANADA AND U.S. BORDER

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For the Degree of Master  
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University of Saskatchewan  
Saskatoon

By

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## **Abstract**

This dissertation focuses on the discontinuity in precipitation measurements across Canada and U.S. border. Incorrect precipitation data may cause inhomogeneous precipitation distribution, which can result in incorrect spatial interpretation. This study quantifies the bias-corrections for the systematic errors (i.e. wind-induced gauge undercatch, wetting loss, and trace precipitation) in the historically national standard manual gauges (Nipher gauge and Type B rain gauge for Canada and NWS 8-inch gauge for U.S.). This study uses the statistical method to compare the measured and corrected precipitation measurements for each pair of the station across the border. It also applies regression analysis to examine the correlation between each station pair and the changes in precipitation relationship due to the bias-corrections. Moreover, a double mass curve (DMC) analysis was conducted to present the changes in cumulative precipitation over time.

Overall, the conclusion of this study is that the bias-correction is greater for NWS 8-inch gauge than for the Canadian Nipher gauge, and also, the bias-correction is higher in the cold season than in the warm season. The DMC also quantifies significant discontinuity in the measurements across Canada and U.S. border. The contributions of this study include: improve the understanding of precipitation change due to the systematic errors (bias-corrections); document the changes in precipitation amounts and distribution due to bias-corrections; and quantify significant discontinuity in the precipitation measurements across Canada and the U.S. border. This study will benefit regional climate and hydrology research.

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***This thesis is dedicated to my mom.***

*For her endless love, support, and encouragement*

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## **Chapter 1. Introduction**

### **1.1 Objective**

Discontinuities in precipitation records across national boundaries exist due to the different instruments and installations (Sanderson, 1975; Yang et al., 2001; Nitu and Wong, 2010). The official definition of discontinuity is ‘a distinct break in physical continuity or sequence in time’ (Oxford Dictionary, 2010). In this study, the discontinuity in precipitation is defined as the difference or break in precipitation measurements between station pair due to bias-corrections. The regional precipitation measurements from various gauges usually cause inhomogeneous precipitation distributions, and these inhomogeneous distributions can result in incorrect spatial interpretation (Yang et al., 2005), especially in windy and cold regions (Scaff et al., 2015). To obtain correct precipitation results, bias-correction must be applied to remove the systematic errors (i.e. wind-induced precipitation undercatch, trace precipitation, wetting loss and evaporation losses) (Yang et al., 1998; Yang et al., 1999; Benning and Yang, 2005; Yang and Ohata, 2000; Metcalfe and Goodison, 1993; Wolff et al. 2015). Although some studies have compared the precipitation across Yukon/Alaska border (Scaff et al., 2015), little work has been done regarding discontinuity in precipitation measurements across Canada and U.S. border of several thousand kilometers. This study is important because the results have considerable influence on regional climate prediction and hydrology research. Also, the results may affect the accuracy of wet deposition calculations (Goodison and Vet, 1989).

The purpose of this thesis is to investigate the discontinuity in precipitation measurements across/along Canada and U.S border. This purpose can be achieved by the following objectives:

1. Quantify changes in precipitation amounts due to the bias-corrections at Canada/U.S. border stations at monthly, seasonal and annual scales;
2. Examine precipitation distribution and its change due to bias-corrections across and along Canada/U.S. border;
3. Explore appropriate methodology to compare and analyze precipitation data across national border.

## **1.2 Precipitation and Observations**

According to World Meteorological Organization (WMO) (2008), precipitation is defined as any form of the condensation of water vapor deposited from atmosphere to the earth's surface. The forms of precipitation include rain, snow, hail, sleet, etc. The amount and duration of precipitation affect human activities, such as agriculture, industry, and environment. For instance, too much precipitation may lead to flooding, and too little precipitation may result in drought. Extreme precipitation may significantly affect agriculture, human, livestock, even organisms. Therefore, it is necessary to monitor the amount and duration of precipitation, and precipitation measurement is essential for climate and hydrology. The most common instrument to measure precipitation is called precipitation gauge; the shape, size, and gauge height vary in different countries (WMO, 2008). The common observation time scales include hourly, three-hourly, six-hourly, twelve-hourly, and daily. The observation time mainly depends on the purpose of the measurement program. Various types of gauges are introduced in Chapter 1.2. As all types of gauges underestimate the true precipitation due to systematic errors, the systematic errors are introduced in Chapter 1.3, and the correction methods are presented in Chapter 1.4.

## **1.3 Gauge Types and Installation Differences**

Since the focus of this study is to investigate the discontinuity in precipitation measurements across Canada and U.S. border, information on different methods of measuring precipitation in the various countries is necessary. The inconsistency in precipitation measurements may occur across national boundaries due to the different instruments used in the various countries (Sanderson, 1975; Yang et al., 2001; Nitu and Wong, 2010; Scaff et al., 2015). First of all, different types of gauges from various countries might cause inconsistency in precipitation

measurements. Table 1-1 shows information of precipitation instruments used in Canada and U.S. (modified from Goodison and Vet, 1989; Environment and Climate Change Canada website; National Weather Service (NWS) website). Figure 1-1 represents three different types of historical national standard manual gauges in Canada and U.S. (Environment and Climate Change Canada website; NWS website). For instance, the standard manual gauge for measuring snowfall over Canada is the Nipher snow gauge (Figure 1-1, left), which has been used in Canadian climate station since 1962 (Metcalf et al., 1997; Yang et al., 2001), and the standard manual gauge for measuring rainfall is the Type B rain gauge (Figure 1-1, middle); however, the standard manual gauge over the U.S. is the NWS 8-inch gauge (Figure 1-1, right) (Metcalf and Goodison, 1993; Mekis and Vincent, 2011; Scaff et al., 2015). Secondly, different installations (Table 1-1) among countries may cause different precipitation measurements. For example, comparing to an unshielded gauge, a shielded gauge can increase 20%-70% catch efficiency for snow precipitation (Larson and Peck, 1974; Yang et al., 1999). Also, the height of the gauge (Table 1-1) may affect the catch efficiency due to the various wind speeds at the different heights.

However, nowadays, the manual gauges are replaced by automatic gauges to measure solid precipitation; therefore, the standard gauges become automatic gauges in many countries. According to Nitu and Wong (2010), 54 WMO member countries reported that 18% of their 41673 operation stations using automatic gauges, and 82% of stations using manual gauges. Moreover, within the automatic gauges, 82.9% of them are tipping bucket gauges, and 16.2% are weighing gauges.

Table 1-1. Information of precipitation instruments used in Canada/U.S. (modified from Goodison and Vet, 1989; Environment and Climate Change Canada website; National Weather Service website)

Gauge Name	Country	Characteristic	Strength
<b>Type B rain gauge</b>	Canada	Orifice diameter: 11.3cm; Orifice area: 100cm <sup>2</sup> ; The gauge is adjusted 40cm above ground.	Minimized systematic errors, especially for wetting loss and evaporation loss.
<b>Nipher Snow gauge</b>	Canada	Vertical copper cylinder diameter: 12.7cm Height: 52cm; Surrounded by the aluminum exponential horn to turn the airflow downward. The gauge is adjusted 150cm above the snow surface.	Minimized the wind turbulence over the top of the gauge; Avoid snow from the ground drift into the gauge.
<b>NWS 8-inch gauge</b>	U.S.	Outer flow can: 8 inches (20.32 cm) in diameter and 24 inches (60.96 cm) tall; Plastic measure tube: 2.5 inches (6.35 cm) in diameter and 20 inches (50.80 cm) tall; Funnel: 8 inches (20.32 cm) in diameter; Installed 40 inches (~100 cm) above ground.	N/A



Figure 1-1. Historical national standard manual gauges: (left) Canadian Nipher snow gauge; (middle) Canadian Type B rain gauge; (right) U.S. NWS 8-inch gauge (Environment and Climate Change Canada website and NWS website).

## 1.4 Systematic Errors

It has been acknowledged that all types of gauges underestimate the true precipitation due to the systematic errors (biases), especially under the cold and windy environment (Legates, 1995; Sevruk, 1989; Goodison et al., 1998; Yang and Ohata, 2000; Yang et al., 2001; Pan et al., 2016). Systematic errors include four factors: wind-induced undercatch, wetting loss, the trace amount of precipitation and evaporation loss (Yang et al., 1999). Firstly, wind speed is the dominant factor that causes precipitation undercatch, and this undercatch is considered as the largest source of the biases, especially for snow measurements (Adam and Lettenmaier, 2003; Wagner, 2009). For example, according to Groisman et al. (1991), the undercatch can be as high as 50% of the precipitation. Also, the wind-induced undercatch depends on gauge type, type of precipitation, gauge height, and wind shield. Secondly, wetting loss occurs when precipitation aggregates on the inside walls of gauges, as well as when the gauge is emptied. The amount of loss varies by gauge type, the precipitation type, and the numbers of time that the gauge is emptied (Yang et al., 1999; Wagner, 2009). Next, the trace amount of precipitation is due to the low-intensity precipitation (Dingman, 1994), and precipitation below the resolution of the gauge (Wagner, 2009). In most cases, trace precipitation is defined as less than 0.005 inch or 0.13 mm (Dingman, 1994; Yang et al., 1999). Nonetheless, the mean rate of trace precipitation also depends on gauge type. According to Yang et al. (1999), there is more total trace precipitation in summer than in winter, but the ratio of trace precipitation to total precipitation is much higher in dry winter than in wet summer over northern regions. Overall, the amount of trace precipitation is significant, especially in low precipitation area (Yang et al., 2001; Sugiura et al., 2003; Wagner, 2009). For instance, Yang et al. (1999) state that the annual corrected trace precipitation was 5% -11% for North Greenland; however, for South Greenland, where there is higher precipitation than North Greenland, the annual corrected trace precipitation is less than 3%. At last, the evaporation loss is generated by the gauge without a funnel in the bucket, and this loss depends on gauge type, climate zone and weather condition (Legates et al., 2005; WMO, 2008; Wagner, 2009).

## 1.5 Bias-correction of Systematic Errors

The general bias-correction equation is shown below (Sevruk, 1982; Yang et al., 1998; Yang and Ohata, 2000):

$$P_c = k(P_g + \Delta P_w + \Delta P_e + \Delta P_t) \dots\dots\dots (1.1)$$

where  $P_c$  = Corrected precipitation

$k$  = Correction coefficient = 100/Catch Ratio

$P_g$  = Gauge-measured precipitation

$\Delta P_w$  = Wetting loss

$\Delta P_e$  = Evaporation loss

$\Delta P_t$  = Trace precipitation

This equation is adaptable to various gauges with their different correction coefficients ( $k$ ). This  $k$  value is a wind-induced coefficient, which is calculated as a function of catch ratio. The calculation of catch ratio for different precipitation conditions and various gauges are introduced in Chapter 1.4.1. Moreover, in different applications, the components in this equation depend on the situation. For example, in this study, the evaporation loss is ignored because of its insignificant value and the lack of information.

As an example, Figure 1-2 represents the contribution of each type of corrections to the total precipitation at two climate stations (Barrow and Nome) in Alaska (Benning and Yang, 2005). First of all, Figure 1-2 indicates that the wind-induced undercatch is the dominant undercatch among the systematic errors, and the trace precipitation makes a large contribution during low precipitation months. Secondly, although these two stations use the same type of gauge (NWS 8-inch gauge), the gauge at Barrow was equipped with an Alter wind shield while the gauge at Nome was unshielded; therefore, Nome station has higher wind losses than Barrow station. Thirdly, as the gauge at Nome station was located on the roof of NWS building, which has higher wind speed; therefore, the wind losses of Nome station are greater than Barrow station. Moreover, this figure also indicates that the bias-corrections depend on the site/location, weather condition, and precipitation types.

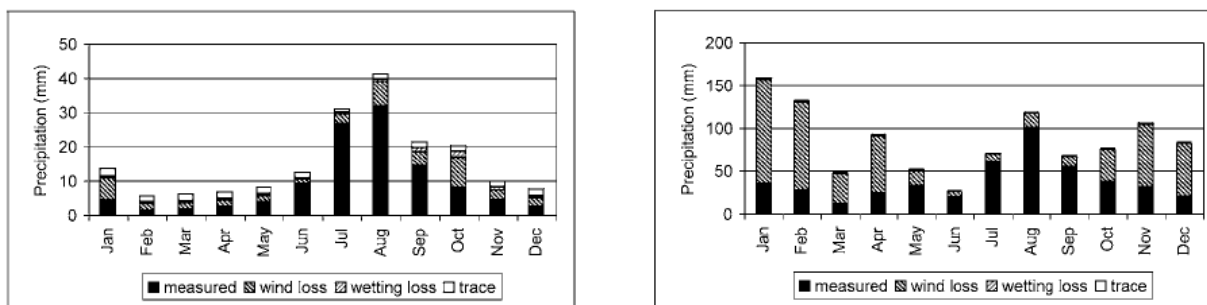


Figure 1-2. Average monthly adjustments for precipitation at Barrow (left) and Nome (Right), Alaska for 1995-2001 (Benning and Yang, 2005).

The correction method for each component is described in this section.

### 1.5.1 Wind-induced Undercatch Correction

To correct wind-induced undercatch, the wind speed at gauge height is required (Yang et al., 1999; Yang and Ohata, 2000). However, when wind speed at the gauge height is not measured, it can be calculated using Equation (1.2) (Yang et al., 1998):

$$U(h) = U(H) \left[ \frac{\ln(h/z_0)}{\ln(H/z_0)} \right] \dots \dots \dots (1.2)$$

where  $U(h)$  = estimated daily wind speed

$U(H)$  = measured daily wind speed at 10 m

$h$  = height of gauge

$H$  = height of anemometer

$z_0$  = roughness parameter

At the same wind speed, because snow has larger surface area per unit mass than rain, the gauge undercatch for snow is much higher than for rain. Therefore, it is necessary to classify the type of the precipitation (Yang et al., 1998; Yang et al., 1999; Yang and Ohata, 2000). The types of precipitation can be determined in different ways. Yang et al. (2005) used daily mean air temperature to estimate precipitation type (rain, mixed and rain) for cold regions. If the temperature is above 2°C, the precipitation is considered as rain; if the temperature is below -2°C, the precipitation is considered as snow; otherwise, the precipitation is mixed. Besides, since blowing snow occurred mostly at higher wind speeds, a threshold wind speed (6.5 m/s) was applied to precipitation events with higher winds (Yang et al., 1999).



The catch ratio of the gauge can be calculated after the wind-speed been determined. However, the catch ratio mainly depends on gauge type, precipitation type, and whether the gauge is shielded. Yang et al. (1998) developed several catch-ratio equations for different conditions for the NWS 8-inch standard gauge:

Snow:

$$R_{Alter\ Shield} = e^{(4.606-0.036Ws^{1.75})} \dots\dots\dots (1.3)$$

$$R_{Unshielded} = e^{(4.606-0.157Ws^{1.28})} \dots\dots\dots (1.4)$$

Mixed Precipitation:

$$R_{Alter\ Shield} = 101.04 - 5.62Ws \dots\dots\dots (1.5)$$

$$R_{Unshielded} = 100.77 - 8.34Ws \dots\dots\dots (1.6)$$

Rain:

$$R_{Alter\ Shield} = e^{(4.606-0.031Ws^{0.69})} \dots\dots\dots (1.7)$$

$$R_{Unshielded} = e^{(4.605-0.062Ws^{0.58})} \dots\dots\dots (1.8)$$

Where  $Ws$  = wind speed (m/s)

Figure 1-3 established the relationship of gauge catch ratio as a function of wind speeds for snowfall (Ryberg et al., 2009). DFIR represents the Double Fence Intercomparison Reference (Yang et al., 1998). Figure 1-3(a) indicates that catch ratio (Nipher/DFIR) versus wind speed at gauge height at seven stations (Goodison et al., 1998). In this figure, a wide range of wind speeds was sampled for snow condition. The scatters show the gauge catch at wind speeds up to 7 m/s. The regression analysis is used to determine the trend of the scatters, which reveals that the catch ratio decreases as the increasing wind speeds in this case. Figure 1-3(b) represents the comparison of the catch ratio of snow as a function of wind speed at gauge height for the Canadian Nipher gauge and the U.S. NWS 8-inch shielded and unshielded gauge during the snowfall (Yang et al., 1998). This figure shows that the catch efficiency mainly depends on gauge types, and the Canadian Nipher has higher catch efficiency than NWS 8-inch gauge during higher wind speed. For example, at the wind speed of 7m/s, the catch ratios for the Canadian Nipher gauge and the

U.S. NWS 8" shielded gauge are about 64% and 32%, respectively. In other words, even at the same location, the measured precipitation is very different by different types of gauge.

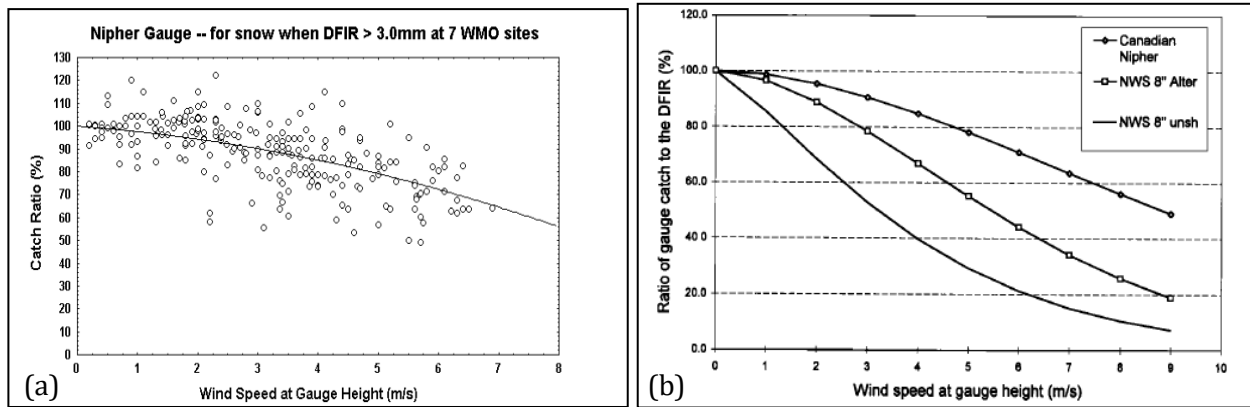


Figure 1-3. (a) Nipher gauge catch ratio (% of DFIR) of daily snow (DFIR > 3.0mm) versus wind speed at the gauge height (Goodison et al., 1998). (b) Comparison of the catch ratio of snow as a function of wind speed at gauge height for the Alter-shielded or unshielded NWS 8-inch standard gauge and the Canadian Nipher snow gauge for snowfall. DFIR represents the Double Fence Intercomparison Reference (Yang et al., 1998).

### 1.5.2 Wetting Losses Correction

The amount of wetting loss depends on the times that the gauge is emptied, gauge type, and precipitation type. Sevruk (1982) reported the following general equation to estimate the amount of wetting loss (Equation 1.9):

$$\Delta P_1 = a_1 \times n_1 \dots \dots \dots (1.9)$$

Where  $\Delta P_1$  = amount of wetting losses

$a_1$  = experimentally estimated average wetting loss per event for a particular collector and form of precipitation

$n_1$  = number of precipitation events with the interval between them greater than the average time needed to dry out the internal walls of the collector (drying time)

It has been documented that the wetting losses are 0.14 mm per observation for rainfall and 0.10 mm per observation for snowfall for the Hellmann gauge (Yang et al., 1999); 0.20 mm per observation for rainfall and 0.15 mm per observation for both snow and mixed precipitation for the Tretyakov gauge (Yang et al. 2000). In this study, for NWS 8-inch gauge, the wetting losses are 0.03 mm per observation for rainfall and 0.15 mm per observation for snowfall.

### **1.5.3 Trace Precipitation Correction**

Trace precipitation losses are calculated on a daily basis, and it is usually corrected by adding the recorded trace amount for each day. According to Woo and Steer (1979), their designed gauge measured the trace rainfall in Canadian High Arctic at the rate of 0.01 mm per day. In this study, the trace precipitation is 0.07 mm per day and 0.10 mm per day for the Nipher snow gauge (Canada) and NWS 8-inch gauge (U.S.), respectively.

### **1.5.4 Evaporation Losses Correction**

As the evaporation loss highly depends on weather condition and site location, there is no general correction equation for calculating this loss (Yang et al., 1995). According to Yang et al. (2001), evaporation losses of the Tretyakov gauge tested in Finland are between 0.30 mm and 0.80 mm per day in summer, and between 0.10 mm and 0.20 mm per day in winter. However, at the same site, the evaporation losses of the Danish Hellmann gauge are between 0.16 mm and 0.27 mm per day in summer, and between 0.03 mm and 0.24 mm per day in winter (Yang et al., 1999).

## Chapter 2. Research Domain, Data And Methods

### 2.1 Study Sites and Region

Figure 2-1 indicates that there are two national boundaries between Canada and the U.S. One is in northwest Canada, the Alaska and Yukon border. The inconsistency in precipitation measurements across this border has been analyzed by Scaff et al. (2015). The study area of this research is the long border in southern Canada (Figure 2-1). The length of this border is about 3987 miles (6416 km) (Beaver, 2006). The study sites include six selected pairs of climate stations across this border (Figure 2-1). Each paired stations contains two manual gauges in Canada and one gauge in U.S., which are the Canadian Nipher gauge and Type B rain gauge, and the NWS 8-inch gauge, respectively. There are three main criteria for selecting the station pairs, i.e. data availability, quality, and distance between stations. Firstly, the selected stations must be confirmed to use the historical national standard manual gauges (Canadian Nipher gauge, Type B rain gauge, and NWS 8-inch gauge). Secondly, the distance between paired station should as short as possible. Thirdly, the overlap period for paired stations must more than one consecutive year. Based on these criteria, the six selected station pairs are shown below (Figure 2-1).



Figure 2-1. Map of six selected pairs of station across and along the border.

## 2.2 Data Source

The original data are from the National Climate Data Center (NCDC), which is the global daily surface dataset archive for more than 8000 stations around the world. The data used in this study are based on the bias-corrected daily precipitation dataset developed in Yang et al. (2005) for the northern regions above 45 °N. The data include daily, monthly and annual precipitation measurements. Each dataset contains temperatures (maximum, minimum, and mean), wind speeds, gauge-measured precipitation, trace precipitation, wetting losses, wind-induced undercatch, and bias-corrected precipitation. To compare precipitation measurements between the paired stations, the overlap time of the paired stations need to be determined. Moreover, the average monthly and annual precipitation measurements during their periods need to be calculated.

Table 2-1 shows the information of the six pairs of selected stations (i.e. Pair No., ID, country, station name, latitude, longitude, elevation, overlap data period and the distance between stations). The data periods range from two to nineteen years for the station pairs, and the periods are long enough to determine the precipitation distribution across the border.

Table 2-1. Information of six pairs of selected stations.

Pair No.	ID (WMO)	Country	Station Name	Lat. (°N)	Long. (°W)	Elevation (m)	Overlap Data Period	Distance (km)
1	718890	CA	Penticton Airport	49.46	-119.60	344	2000-2005	117
	727890	U.S.	Omak	48.41	-119.53	382		
2	711540	CA	Waterton Park Gate	49.13	-113.80	1296	1995-2000	120
	727796	U.S.	Cut Bank	48.60	-112.36	1169		
3	741350	CA	Rockglen	49.16	-105.98	915	1974-1976	116
	727680	U.S.	Glasgow International Airport	48.21	-106.61	699		
4	718620	CA	Estevan Airport	49.21	-102.96	581	1980-1998	123
	727670	U.S.	Williston-Sloulin Field International Airport	48.20	-103.65	580		
5	712600	CA	Sault Ste Marie	46.48	-84.51	192	1997-1998	105
	727347	U.S.	Pellston Emmet County	45.57	-84.79	217		
6	717000	CA	Fredericton Airport	45.88	-66.53	20	2000-2007	102
	727033	U.S.	Houlton International Airport	46.12	-67.79	150		

## 2.3 Data Analysis Methods

This study uses statistical methods to analyze the difference between measured and bias-corrected precipitation data. These analyses are used for both monthly and annual precipitation data for each paired stations, and also for daily data for two station pairs (Estevan Airport and Williston-Sloulin Field International Airport stations, Fredericton Airport and Houlton International Airport stations). The basic analysis is used to compare the measured data and corrected data for each station and to determine how much precipitation increases from measured data to corrected data. Besides, how the precipitation distributions change over time, how the precipitation distributions change across/along the Canada/U.S. border, and whether the precipitation distribution corresponds with temperature and wind speed. Moreover, to determine the seasonal precipitation distribution, this study divides the seasons into two categories based on the temperature: warm months (temperature  $> 0^{\circ}\text{C}$ ) and cold months (temperature  $\leq 0^{\circ}\text{C}$ ).

### 2.3.1 Statistical Analysis

For monthly precipitation, the collected monthly data for each station are separated into different categories based on the months (from January to December). Then, temperature, wind speeds, measured and corrected precipitation is averaged for each month. According to the information, the “Mean Monthly Precipitation” and “Mean Wind Speed/Air Temperature” diagrams can be plotted. In the plots, the monthly measured and corrected precipitation over the data period can be displayed, and the average bias-corrections for each month can be shown as well. Besides, the corresponding wind speed and air temperature can be plotted. When these two plots are combined, the precipitation distributions in cold months and warm months can be analyzed, and whether the precipitation distribution is affected by wind speed and air temperature can be also determined. Besides, the monthly precipitation (February and July) at two paired stations over data period is plotted separately, so as to compare the bias-corrections between stations and months; moreover, these plots can reflect the precipitation distribution over time for specific months. For annual precipitation, the monthly measured and corrected precipitation is summed to yearly totals and then plotted for each station over the data period. The results reflect the annual precipitation distribution over time, and also represent the bias-corrections for each year at each station. For daily precipitation, the probability density function plots for the measured and corrected precipitation at paired stations indicates the probability of daily precipitation for each station, and how the probability changes due to bias-corrections. Also, the maximum daily precipitation (in warm

and cold seasons, separately) for each year over data period is plotted for the paired stations, with their corresponding wind speeds. The results compare the bias-corrections for the warm and cold seasons at each station and the bias-corrections between stations pairs as well.

### **2.3.2 Regression Analysis**

Regression analysis can be used to determine the relationship between the measurements in two gauges. Figure 2-2 shows that the comparison between the Danish Hellmann gauge and Hungarian Helmmann gauge for snow measurements (Goodison et al., 1998). This figure indicates that the ratio of the measurements between these two gauges is almost 1:1, which means they caught the similar amount of snowfall. However, if the ratio between two gauges is not close to 1, it means the measurements of one gauge are higher than the other gauge. The regression analyses are used in this study to determine if a relationship between the paired stations for both measured and corrected precipitation. In this analysis, the monthly precipitation data of paired stations are divided into cold months (Temperature  $\leq 0^{\circ}\text{C}$ ) and warm months (Temperature  $> 0^{\circ}\text{C}$ ). Then, the data are used to generate cold and warm months' scatter plots, respectively. The scatter plots reveal which station has higher precipitation measurements, and the R-squared statistic of the regression lines indicate the precipitation relationship between two stations. If the  $R^2$  value is small, it suggests a weak relationship between the two stations; while the  $R^2$  is large, it means a strong relationship. Then, the regression lines are determined by the measured and corrected data, so as to see how the lines shift from the corrected to the measured data. For instance, the small upward shift or no shift from the measured to corrected precipitation indicates a small or no precipitation difference between the measured and corrected data; otherwise, it indicates a significant precipitation difference between the data.

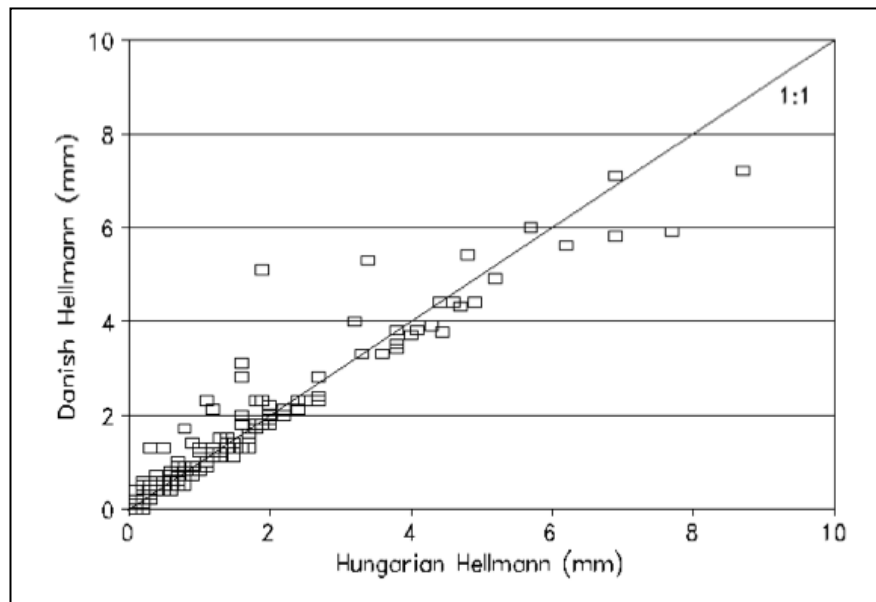


Figure 2-2. Comparison between Danish Hellmann gauge and Hungarian Hellman gauge for snow measurement at Jokioinen WMO Intercomparison station (Goodison et al., 1998).

### 2.3.3 Double Mass Curve (DMC)

The double mass curve (DMC) is a useful tool to assess the discontinuity of the precipitation measurements over time (Searcy and Hardison, 1960; Dingman, 1994). In this study, the DMC analysis indicates the significant differences in the precipitation accumulation between the station pair. Firstly, the monthly measured and corrected precipitation data for each station are added month by month. Then, the accumulated data for paired stations are plotted and compared. If a DMC shows a straight line between two cumulative data of variables, it means the relation between these two variables is a fixed ratio (Searcy and Hardison, 1960); in other words, if the DMC has a constant slope, the records of two stations are consistent over time. However, breaks in DMC represent that the relationship between the two variables changed. The breaks may be due to the climatic shift or measurement condition change (Dingman, 1994); in another word, if DMC has a break, the records of two stations are inconstant and need to be adjusted. However, the adjusting only needs to be done when there is authentic evidence show that the change is caused by measurement condition changed (Dingman, 1994). Furthermore, the different slopes of the curves stand for the degree of changes in relations (Searcy and Hardison, 1960). If the slope keeps changing over time, that means the relationship between stations keeps changing, which implies the existence of discontinuity in precipitation measurements across the border.



## **Chapter 3. Results for Station Pairs**

In this chapter, the results are shown following the station pairs from west to east along the Canada and U.S. border. The results include monthly precipitation, annual precipitation, seasonal precipitation, monthly precipitation relationship and accumulative monthly precipitation for each station pair. Furthermore, the results include daily precipitation for two station pairs (pair 4 and pair 6).

### **3.1 Penticton Airport (CA) and Omak (U.S.) stations**

Penticton Airport station is located in British Columbia province in Canada. Its geographical coordinates are 49.46N, -119.60W, and its elevation is 344 m (Environment Canada, 2016). This station has a cold semi-arid steppe climate. Within 40 km of this station, the region is covered by forests (88%), grasslands (7%), and lakes and rivers (4%). The surrounding lakes are Okanagan Lake and Skaha Lake (Peel et al, 2007).

Omak station is located in Washington, D.C. in U.S. Its geographical coordinates are 48.41N, -119.53W, and its elevation is 382 m (National Oceanic and Atmospheric Administration (NOAA)). This station has a cold semi-arid steppe climate. Within 40 km of this station, the region is covered by grasslands (52%) and forests (47%) (Peel et al, 2007).

The original data used for this paired stations are monthly measured and corrected precipitation data from 2000 to 2005. Moreover, the distance between these two stations is 117km.

#### **3.1.1 Monthly Precipitation**

Figure 3-1 shows the mean monthly precipitation plots and their corresponding wind speed and air temperature for Penticton Airport station (Canada) and Omak station (U.S.) during 2000-2005. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. According to temperature, the only cold month ( $T \leq 0^{\circ}\text{C}$ ) for Penticton Airport station is January; the warm months ( $T > 0^{\circ}\text{C}$ ) are from February to December. However, the cold months for Omak

station are from December to February, and the warm months are from March to November. The upper two plots display that the mean monthly precipitation distributions of these two stations are different. For instance, the peak of monthly precipitation for Penticton Airport station occurs in June; however, the highest monthly precipitation for Omak station occurs in December.

For Penticton Airport station in Canada (Figure 3-1), the peaks of monthly measured and corrected precipitation during the annual cycle both occur in June (39 mm and 40 mm, respectively), corresponding to the high air temperature and low wind speed. The lowest measured and corrected precipitation both occur in February (12 mm and 13 mm, respectively), which correspond to the relative high wind speed and low air temperature. The measured precipitation ranges from 12 mm to 39 mm for rain, and about 25 mm for snow. The corrections increase precipitation by about 1 mm - 2 mm for rain, and 2 mm for snow, which mean that the relative increases are 2% - 6% for rain, and 8% for snow.

For Omak station in U.S. (Figure 3-1), the peaks of monthly measured and corrected precipitation during annual cycle both occur in December (50 mm and 58 mm, respectively), which correspond to low wind speed. The lowest measured and corrected precipitation both occur in September (both 5 mm). The measured precipitation ranges from 5 mm to 32 mm for rain, and from 14 mm to 50 mm for snow. The corrections increase precipitation by about 5 mm to 35 mm for rain, and 16 mm to 58 mm for snow, or relative increases of 10% - 16% for rain and 15% - 16% for snow. The results indicate that the precipitation at this station is much higher in the cold months than in the warm months. For instance, the average corrected precipitation in the warm months is 18 mm, but the average corrected precipitation in the cold months is 35 mm, almost twice as the average precipitation in the warm months.

Overall, precipitation measurements at Penticton Airport station is more even than at Omak station throughout the year. Also, the average bias-correction for Penticton Airport station (4%) is lower than Omak station (12%). Besides, for both stations, the bias-corrections are higher in the cold months than in the warm months. The lower correction percentages for Penticton Airport station (Canada) are mainly due to the lower undercatch of the Nipher snow gauge, and the lower wind speeds in the cold months as well.

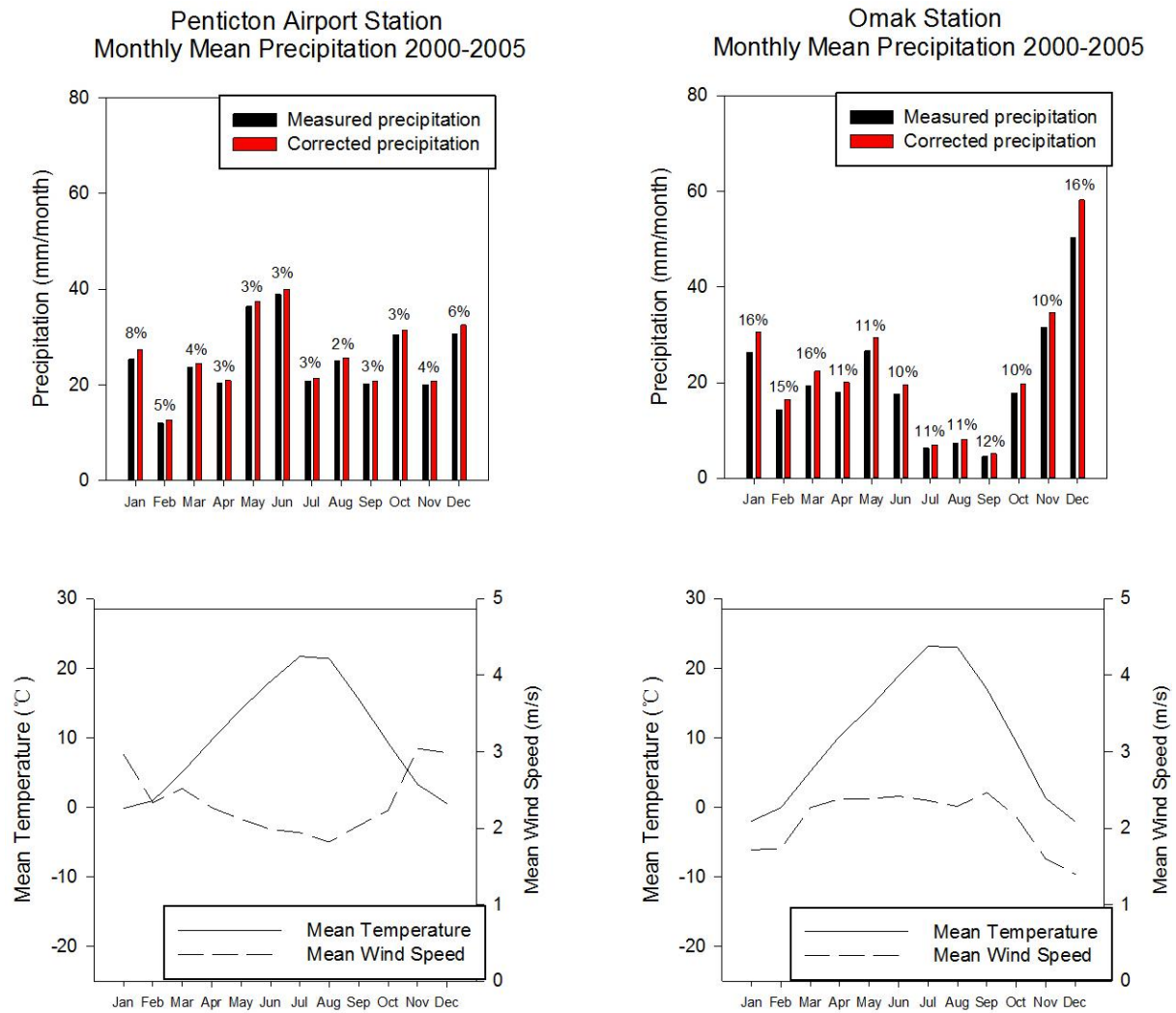


Figure 3-1. Mean monthly precipitation at Penticton Airport station and Omak station, and the corresponding mean monthly wind speed/air temperature (bottom panels) during 2000-2005. The percentage of each bar group represents the bias-correction change for that month.

### 3.1.2 Annual Precipitation

Figure 3-2 represents the annual precipitation at Penticton Airport station and Omak station during 2000-2005. The percentage of each bar group represents the bias-correction change for that year. The annual maximum and minimum precipitation (both measured and corrected precipitation) for Penticton station occurs in 2004 and 2002, respectively. The annual maximum and minimum precipitation (both measured and corrected precipitation) for Omak station occurs in 2005 and 2000, respectively. For Penticton Airport station, the bias-correction for each year is only between 3% and 4%. However, for Omak station, the bias-corrections range from 10% to 16%. Over the six years, the average percentages of Penticton Airport and Omak stations are 4% and 12%; therefore, the bias-corrections are much higher at Omak station than at Penticton Airport station.

According to Henry (1919), precipitation increases with altitude in most regions. The difference of precipitation measurements between these two stations may due to their different elevations: the elevation of Penticton Airport station is 344 m, and the elevation of Omak station is 382 m. Furthermore, the Penticton Airport station is close to Okanagan Lake and Skaha Lake; and the Omak station is close to Omak Lake, Crawfish Lake, Moses Mountain and Omak Mountain. Besides, within 40 km around the stations, the Penticton Airport station is covered 88% by forest, which is 41% more than Omak station (47%). As the forest cover can enhance the rainfall (Makarieva and Gorshkov, 2007; Sheil and Murdiyarso, 2009), the rainfall at Penticton Airport station is more than at Omak station.

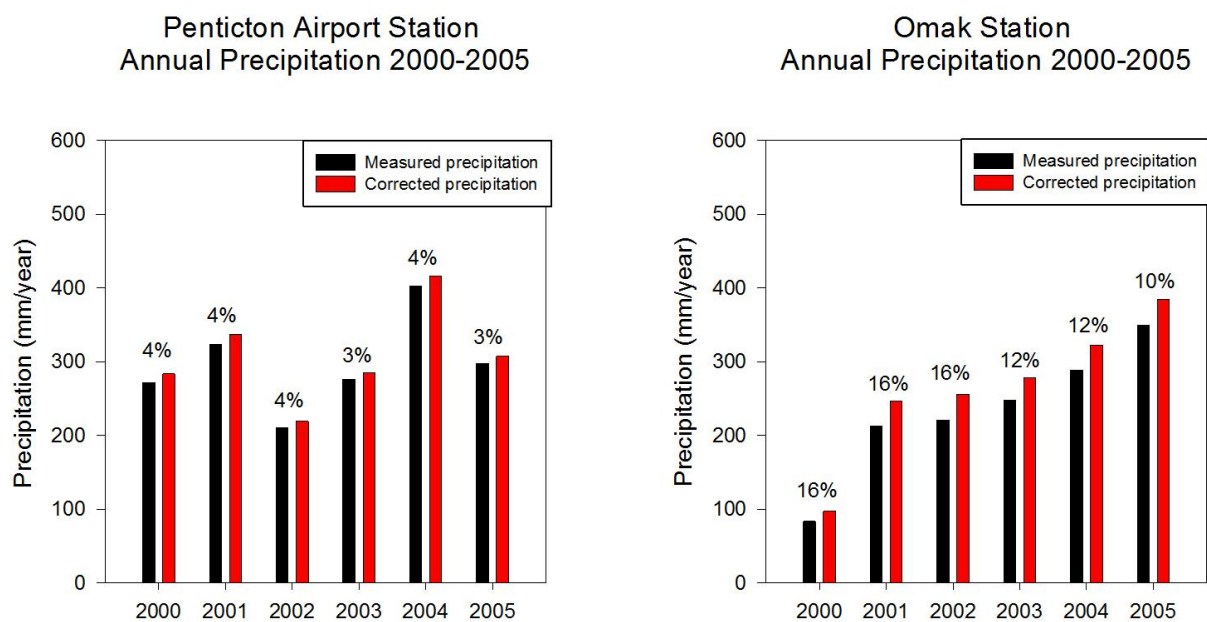


Figure 3-2. Annual measured and corrected precipitations for Penticton Airport station and Omak station during 2000-2005. The percentage on each bar group represents the bias-correction change for that year.

### 3.1.3 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-3 shows the mean annual measured and corrected precipitation for the cold and warm months at Penticton Airport station and Omak station. The percentages are the total changes from measured to corrected precipitation relative to the amount of measured precipitation. This figure displays that the total measured precipitation for Penticton Airport station and Omak station is 304 mm and 240 mm, respectively; the total corrected precipitation for Penticton Airport station and Omak station is 315 mm and 271 mm, respectively. These data display that both measured and corrected precipitation is higher at Penticton Airport station than at Omak station. Also, the overall bias-corrections are 3.7% for Penticton Airport station and 12.9% for Omak station. Within these data, the changes in the warm months are 3.3% for

Penticton Airport station and 11.2% for Omak station; the changes in the cold months are 8.1% for Penticton Airport station and 15.7% for Omak Airport station. Overall, these results indicate that the Omak station has higher bias-corrections than Penticton Airport station, especially for cold months. These changes are mainly caused by the high undercatch for snowfall measurements. Moreover, as these two stations are located 117 km apart, the precipitation difference between them may also be caused by the spatial distribution (Yang et al., 2003).

Mean Annual Measured/Corrected Precipitation for Cold/Warm Months

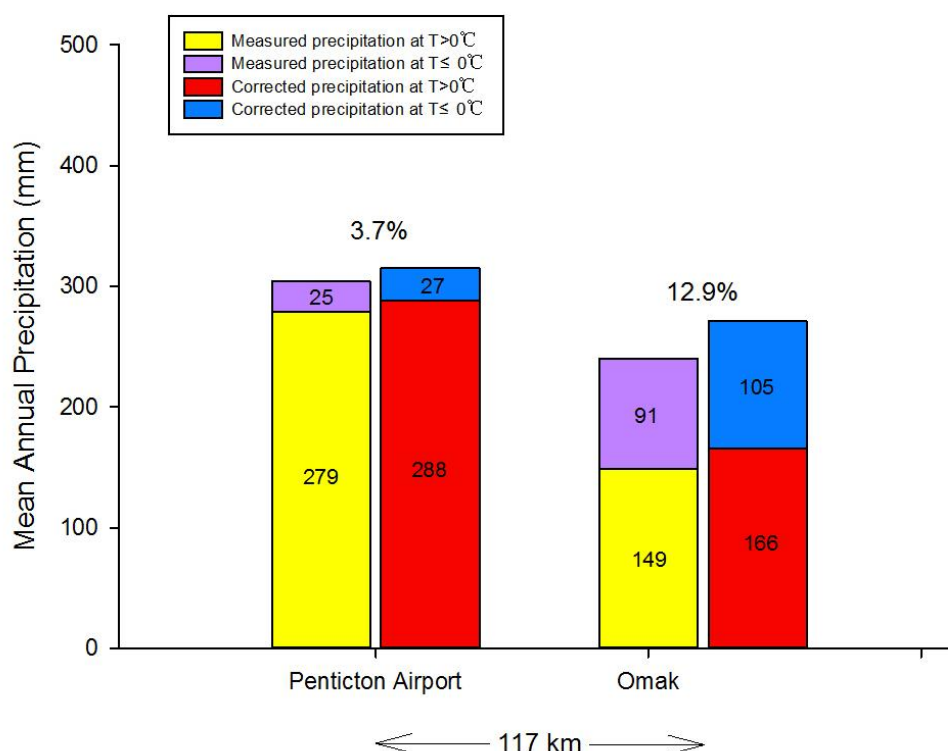


Figure 3-3. Mean annual measured and corrected precipitation for cold ( $\text{Temp} \leq 0^\circ\text{C}$ ) and warm ( $\text{Temp} > 0^\circ\text{C}$ ) months at Penticton Airport station and Omak station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the stations.

### 3.1.4 Monthly Precipitation Relationship

Figure 3-4 illustrates the scatter plots of corresponding monthly precipitation for Penticton Airport station and Omak station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. The left plot displays that the  $R^2$  for measured and corrected precipitation are both 0.23; the right plot displays that the  $R^2$  for measured and corrected precipitation are 0.38 and 0.32, respectively. The results suggest that the relationships

between these two stations are weak in both warm and cold months; however, the relationships are relatively stronger in the cold months than the in warm months, for both measured and corrected data. Also, according to the shifts of the regression lines, the difference between measured and corrected precipitation is small in both warm and cold months, but still slightly higher in the warm months than in the cold months.

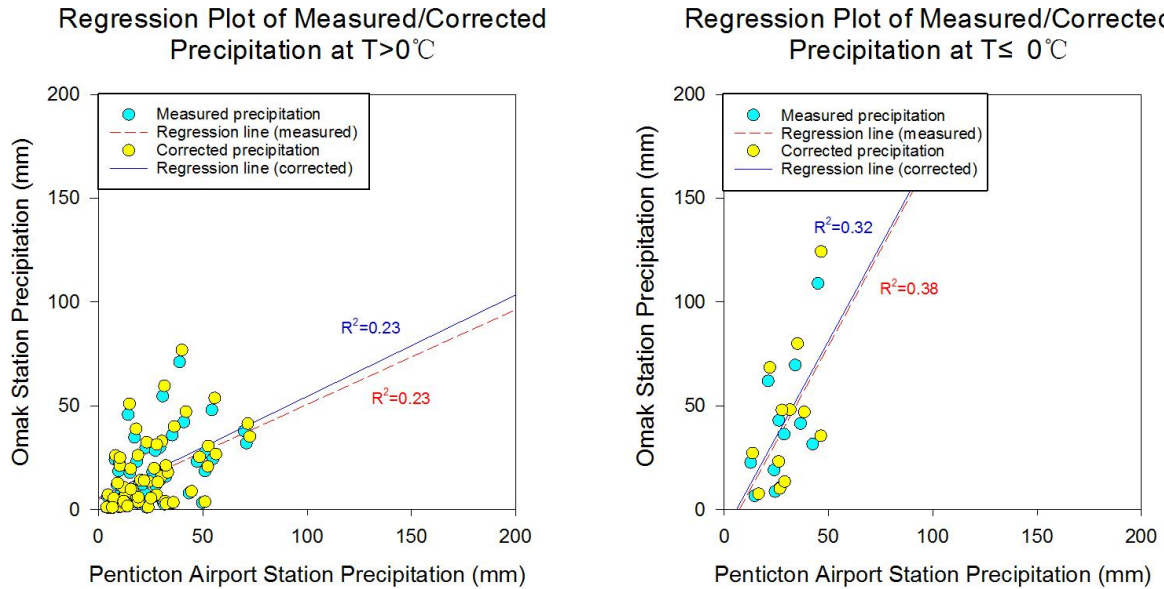


Figure 3-4. Scatter plots of corresponding monthly precipitation for Penticton Airport station and Omak station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months.

### 3.1.5 Accumulation of Monthly Precipitation

Figure 3-5 represents the DMCs between Penticton Airport station (Canada) and Omak station (U.S.) during 2000-2005. This plot indicates that both accumulated measured and corrected precipitation is higher at Penticton Airport station than at Omak station. Also, the slopes of both curves are not constant, indicating the relationships between the two stations are not constant for both measured and corrected precipitation. Moreover, the changing slopes indicate the existence of discontinuity in precipitation across the border. Figure 3-5 shows that the slopes for both measured and corrected precipitation changed four times during these six years. At the end points, from the measured precipitation to corrected precipitation, the point shifts more upward than to the right side, implying that the bias-corrections are higher at the Omak station than at Penticton Airport station. Also, at the end points, the difference of measured precipitation between these two stations is about 379 mm; however, the difference of corrected precipitation between these two stations decreases to 263 mm. Therefore, it reveals that the observed (measured) precipitation difference overestimates the precipitation difference between the paired stations.

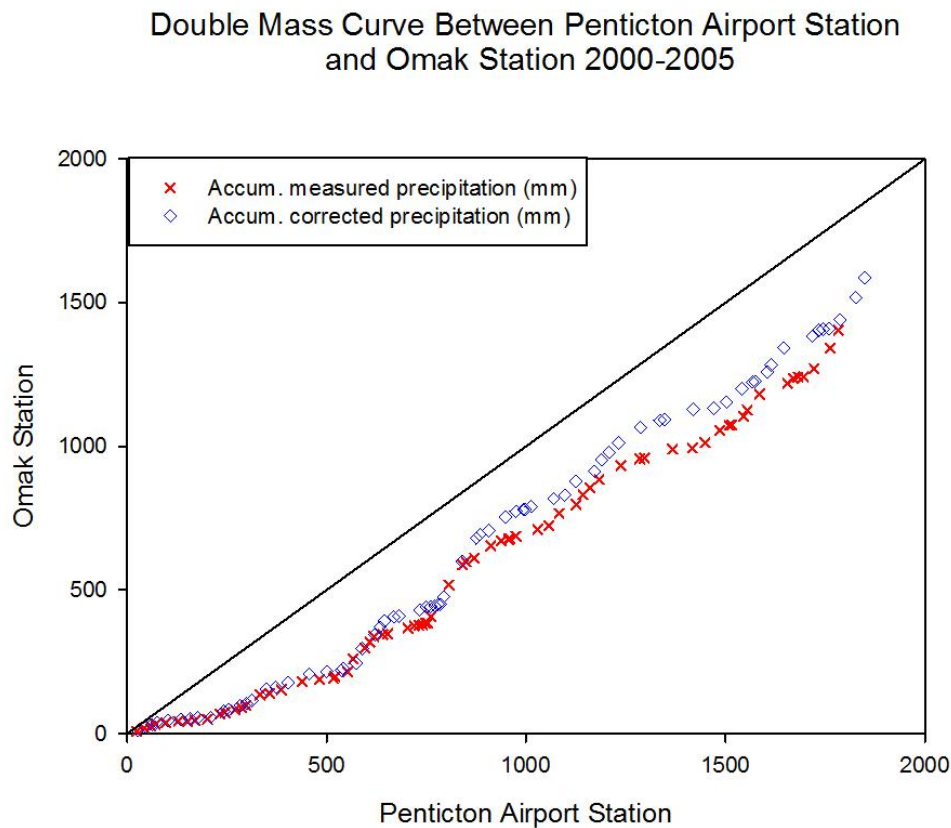


Figure 3-5. Double mass curve between Penticton Airport station and Omak station during 2000-2005.



## **3.2 Waterton Park Gate (CA) and Cut Bank (U.S.) stations**

Waterton Park Gate station is located in Alberta province in Canada. Its geographical coordinates are 59.13N, -113.80W, and its elevation is 1296 m (Environment Canada, 2016). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by forests (61%) and croplands (35%) (Peel et al, 2007).

Cut Bank station is located in Montana State in U.S. Its geographical coordinates are 48.60N, -112.36W, and its elevation is 1169 m (NOAA). This station has a cold semi-arid steppe climate. Within 40 km of this station, the region is covered by grasslands (91%), forests (3%), and croplands (3%) (Peel et al, 2007).

The original data used for this paired stations are monthly measured and corrected precipitation data from 1996-2000. Moreover, the distance between these two stations is 120km.

### **3.2.1 Monthly Precipitation**

Figure 3-6 shows the mean monthly precipitation and wind speed and air temperature for Waterton Park Gate station (Canada) and Cut Bank station (U.S.) during 1996-2000. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. According to temperature, the cold months for both stations are from November to March, and the warm months are from April to October. The upper two plots display that the mean monthly precipitation distributions of these two stations are different. For instance, the peak of monthly precipitation for Waterton Park Gate station occurs in May; however, the highest monthly precipitation for Cut Bank station occurs in June.

For Waterton Park Gate station in Canada (Figure 3-6), the peaks of monthly measured and corrected precipitation both occur in May (94 mm and 97 mm, respectively); the lowest measured and corrected precipitation occurs in July (both 11 mm). The measured precipitation ranges from 11 mm to 94 mm for rain, and from 22 mm to 75 mm for snow. The corrections increase precipitation by about 0 to 3 mm for rain, and 2 mm to 7 mm for snow, which mean that the relative increases are 2% - 8% for rain, and 5% - 19% for snow. The results indicate that the bias-corrections at this station are higher in the cold months than in the warm months.



For Cut Bank station in U.S. (Figure 3-6), the peaks of monthly measured and corrected precipitation both occur in June (56 mm and 64 mm, respectively); the lowest measured and corrected precipitation occurs in February (4 mm and 7 mm, respectively), which correspond to the high wind speed and low air temperature. The measured precipitation ranges from 6 mm to 56 mm for rain, and from 4 mm to 13 mm for snow. The corrections increase precipitation by about 2 mm to 10 mm for rain, and 3 mm to 8 mm for snow, or relative increases of 11% - 52% for rain and 34% - 82% for snow. The results indicate that the bias-corrections at this station are higher in the cold months than in the warm months.

Overall, the average bias-correction for Waterton Park Gate station (7%) is much lower than Cut Bank station (37%). Also, for both stations, the bias-corrections are higher in the cold months than in the warm months, especially at Cut Bank station. The lower correction percentages for Penticton Airport station (Canada) are mainly due to the lower undercatch of the Nipher snow gauge, and also the lower wind speeds in the cold months.

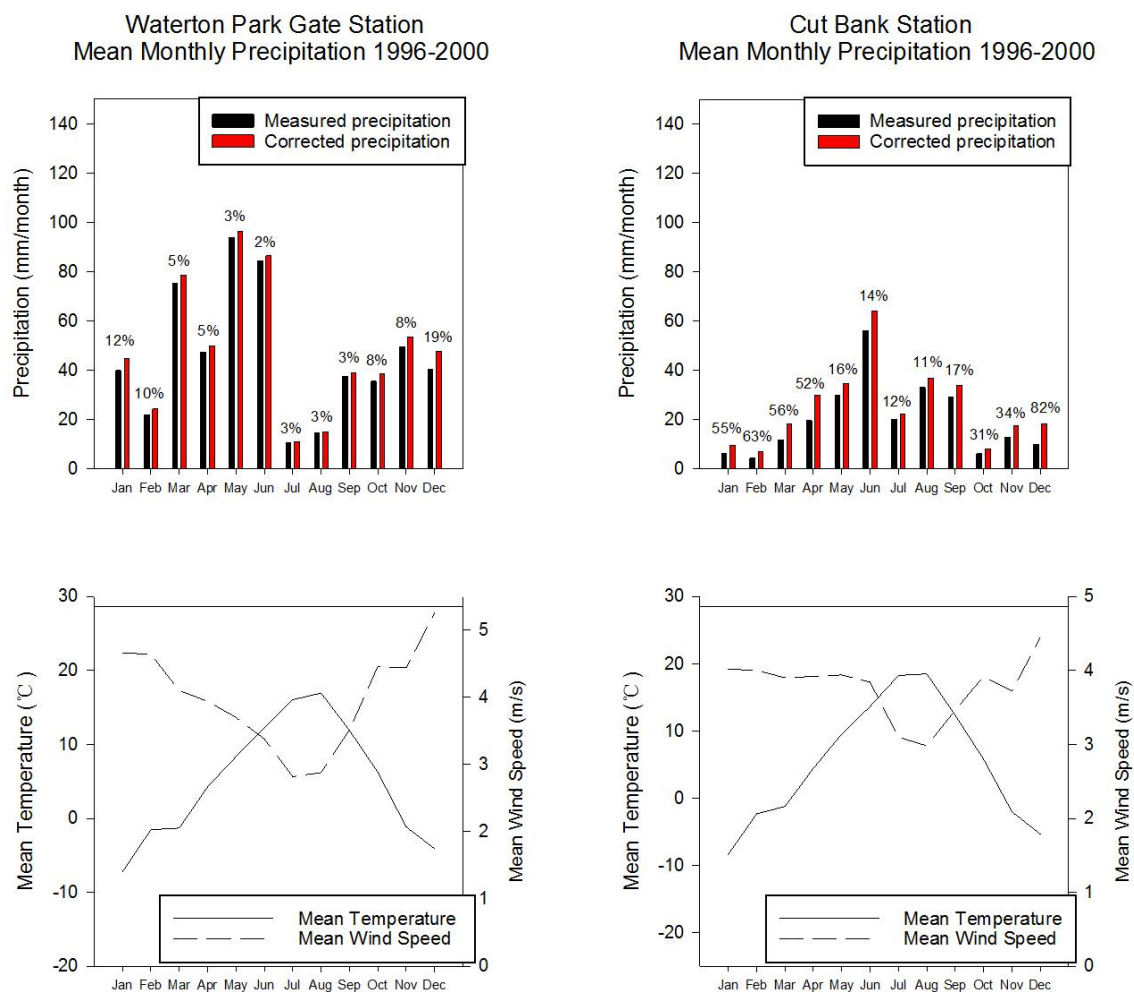


Figure 3-6. Mean monthly precipitation at Waterton Park Gate station and Cut Bank station, and the corresponding mean monthly wind speed/air temperature (bottom panels) during 1996-2000. The percentage of each bar group represents the bias-correction change for that month.

### 3.2.2 Annual Precipitation

Figure 3-7 represents the annual precipitation at Waterton Park Gate station and Cut Bank station during 1996-2000. The percentage of each bar group represents the bias-correction change for that year. The annual maximum and minimum precipitation (both measured and corrected precipitation) for Waterton Park Gate station occurs in 1997 and 2000, respectively. The maximum annual precipitation (both measured and corrected precipitation) for Cut Bank station occurs in 1998 and 2000, respectively. For Waterton Park Gate station, the bias-correction for each year is only between 4% and 9%. However, for Cut Bank station, the bias-corrections range from 22% to 29%. Therefore, the bias-corrections are much higher at Cut Bank station than at Waterton Park Gate station.

According to Henry (1919), precipitation increases with altitude in most regions. The difference of precipitation measurements between these two stations may due to their different elevations: the elevation of Waterton Park Gate station is 1296 m, and the elevation of Cut Bank station is 1169 m. Furthermore, the Waterton Park Gate station is in the region that covered 61% by forest; however, the Cut Bank station is in the region that only covered 3% by forest. As the forest cover can enhance the rainfall (Makarieva and Gorshkov, 2007; Sheil and Murdiyarso, 2009), the rainfall at Waterton Park station is more than at Cut Bank station.

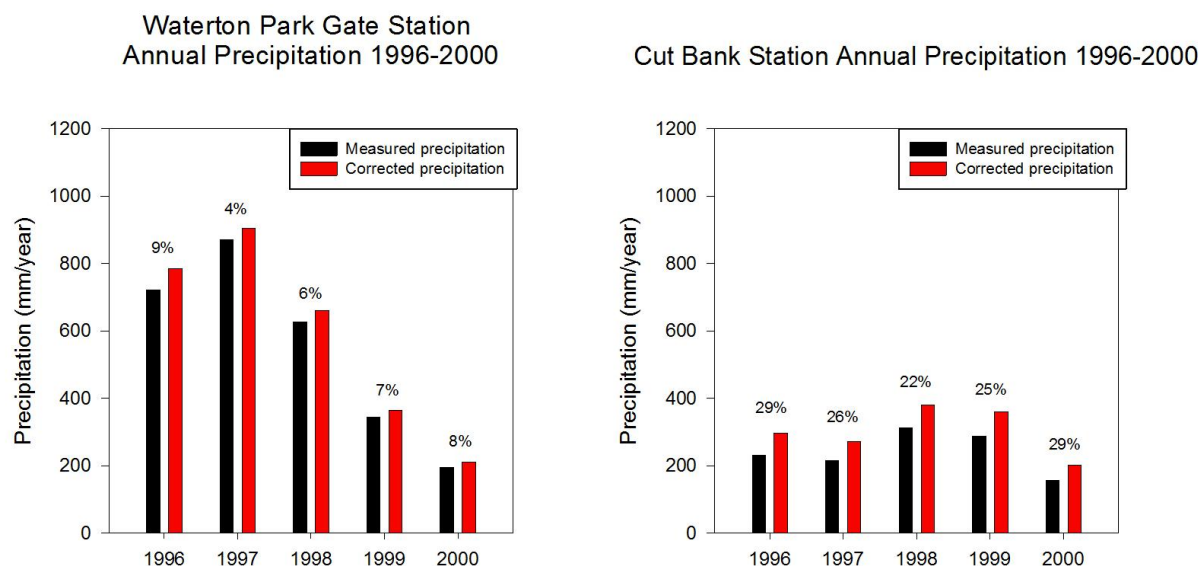


Figure 3-7. Annual measured and corrected precipitations for Waterton Park Gate station and Cut Bank station during 1996-2000. The percentage of each bar group represents the bias-correction change for that year.

### 3.2.3 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-8 shows the mean annual measured and corrected precipitation for the cold and warm months at Waterton Park Gate station and Cut Bank station. The percentages are the total changes from measured to corrected precipitation relative to the amount of measured precipitation. This figure displays that the total measured precipitation for Waterton Park Gate station and Cut Bank station is 552 mm and 241 mm, respectively; the total corrected precipitation for Waterton Park Gate station and Cut Bank station is 586 mm and 302 mm, respectively. These data show that both measured and corrected precipitation is higher at Waterton Park Gate station than at Cut Bank station, which is mainly due to their different climate types (Waterton Park Gate station has a humid continental climate; Cut Bank station has a cold semi-arid steppe climate). Besides, the overall corrections from measured to corrected precipitation are 6.1% for Waterton Park Gate station and 25.6% for Cut Bank station. Within these data, the changes in the warm months are 3.6% for Waterton Park Gate

station and 18.4% for Cut Bank station; the changes in the cold months are 9.7% for Waterton Park Gate station and 56.0% for Cut Bank station. Overall, these results indicate that the Cut Bank station has higher bias-corrections than Waterton Park Gate station, especially for cold months. These changes are mainly caused by the high undercatch for snowfall measurements. Besides, as these two stations are located 120 km apart, the precipitation difference between them maybe also due to the spatial distribution (Yang et al., 2003).

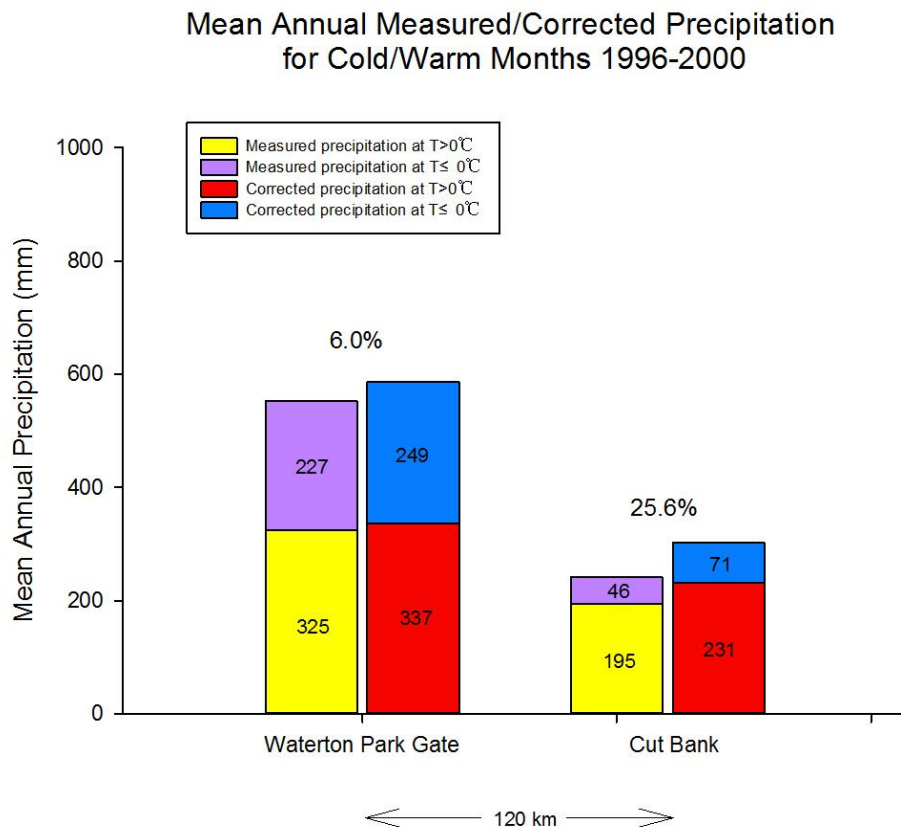


Figure 3-8. Mean annual measured and corrected precipitation for cold ( $\text{Temp} \leq 0^\circ\text{C}$ ) and warm ( $\text{Temp} > 0^\circ\text{C}$ ) months at Waterton Park Gate station and Cut Bank station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the stations.

### 3.2.4 Monthly Precipitation Relationship

Figure 3-9 illustrates the scatter plots of corresponding monthly precipitation for Waterton Park Gate station and Cut Bank station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. The left plot displays that the  $R^2$  for measured and corrected precipitation are 0.33 and 0.32. The  $R^2$  values suggest that the relationships between these two stations are weak for the warm months. As the regression curve for the cold months did not make sense, it did not show in the plot. Also, according to the shifts of the regression lines, the difference between measured and corrected precipitation is small in the warm months.

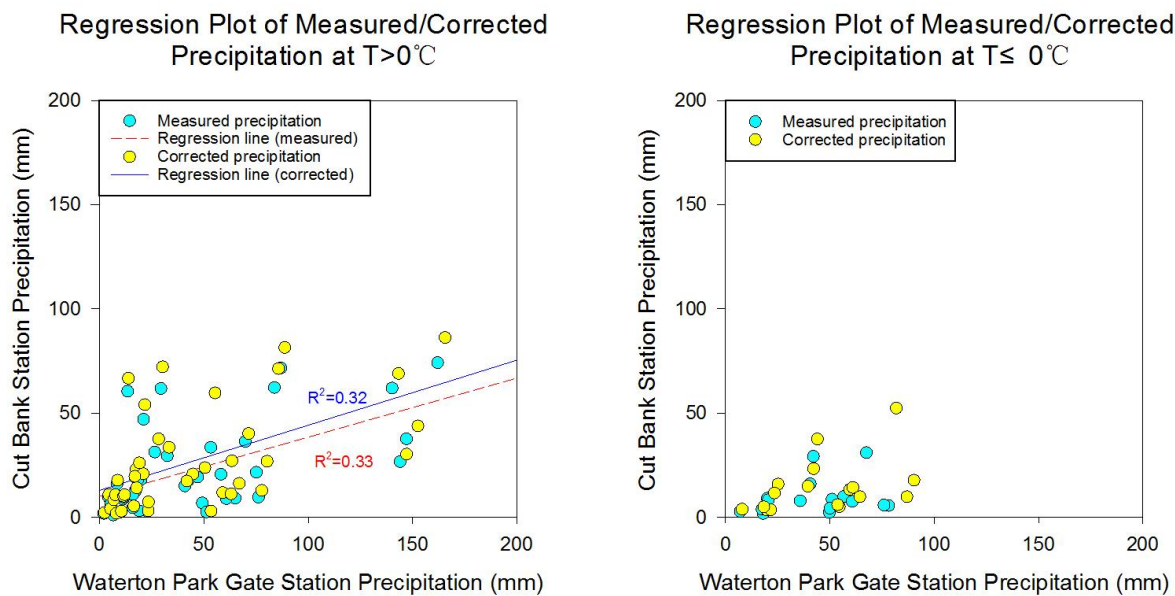


Figure 3-9. Scatter plots of corresponding monthly precipitation for Waterton Park Gate station and Cut Bank station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months.

### 3.2.5 Accumulation of Monthly Precipitation

Figure 3-10 represents the DMCs between Waterton Park Gate station (Canada) and Cut Bank station (U.S.) during 1996-2000. This plot indicates that both accumulated measured and corrected precipitation is much higher at Waterton Park Gate station than at Cut Bank station. Also, the slopes of both curves are not constant, indicating the relationships between the two stations for both measured and corrected precipitation are not constant. Moreover, the changing slopes indicate the existence of discontinuity in precipitation across the border. According to Figure 3-10, the slopes for both measured and corrected precipitation changed twice sharply during these six years. Based on the archives, these changes occur in July 1998

and June 1999. At the end points, from the measured precipitation to corrected precipitation, the point shifts more upward than to the right side, indicating the bias-corrections are higher at the Cut Bank station than at Waterton Park Gate station. Besides, at the end points, the difference of measured precipitation between these two stations is about 1557 mm; however, the difference of corrected precipitation between these two stations decreases to 1418 mm. Therefore, it reveals that the observed (measured) precipitation difference overestimates the precipitation difference between the paired stations.

**Double Mass Curve Between Waterton Park Gate Station  
and Cut Bank Station 1996-2000**

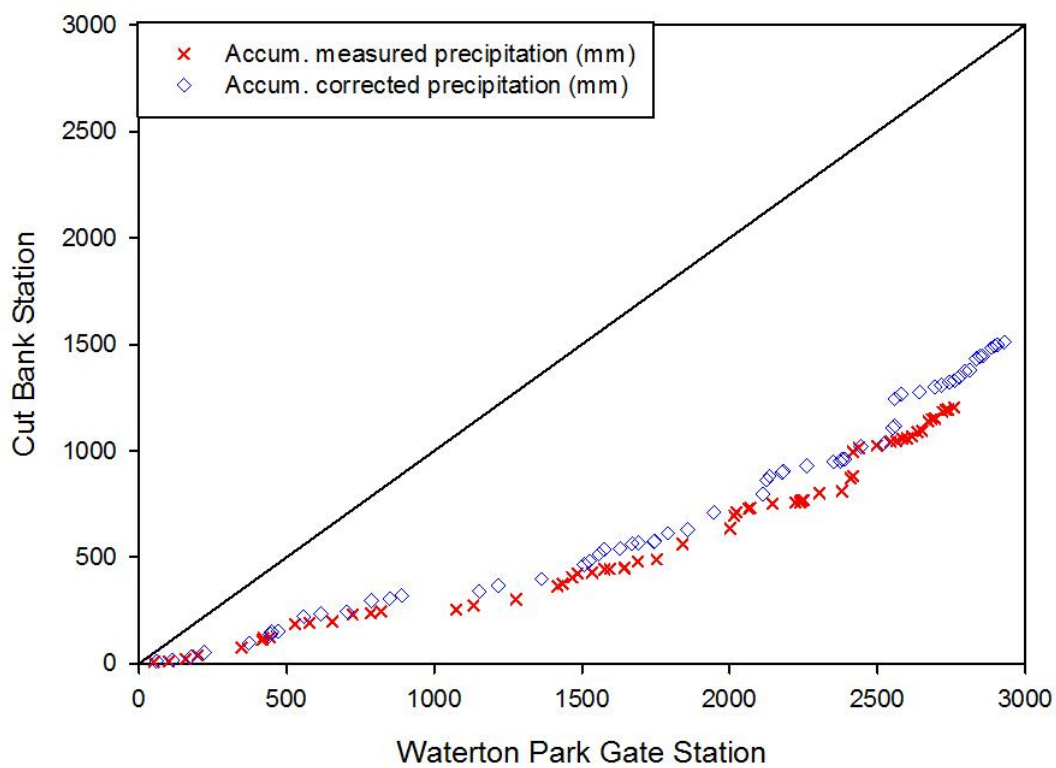


Figure 3-10. Double mass curve between Waterton Park Gate station and Cut Bank station during 1996 – 2000.

### **3.3 Rockglen (CA) and Glasgow International Airport (U.S.) stations**

Rockglen station is located in Saskatchewan province in Canada. Its geographical coordinates are 49.16N, -105.98W, and its elevation is 915 m (Environment Canada, 2016). This station has a cold semi-arid steppe climate. Within 40 km of this station, the region is covered by grasslands (98%) (Peel et al, 2007).

Glasgow International Airport station is located in Montana in U.S. Its geographical coordinates are 48.21N, -106.61W, and its elevation is 699 m (NOAA). This station has a cold semi-arid steppe climate. Within 40 km of this station, the region is covered by grasslands (47%), shrublands (46%), lakes and rivers (5%), and croplands (2%) (Peel et al, 2007).

The original data used for this paired stations are monthly measured and corrected precipitation data from 1974-1976. Moreover, the distance between these two stations is 116km.

#### **3.3.1 Monthly Precipitation**

Figure 3-11 shows the mean monthly precipitation and wind speed and air temperature for Rockglen station (Canada) and Glasgow International Airport station (U.S.) during 1974-1976. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. According to temperature, the cold months for both stations are from November to March, and the warm months are from April to October. The upper two plots display that the mean monthly precipitation distributions of these two stations are different. For instance, the precipitation in February is very high at Rockglen station but very low at Glasgow International Airport station.

For Rockglen station in Canada (Figure 3-11), the peaks of monthly measured and corrected precipitation occur in June (78 mm) and March (109 mm), respectively. The lowest measured and corrected precipitation occurs in November (15 mm) and September (21 mm), respectively. The measured precipitation ranges from 19 mm to 78 mm for rain, and from 15 mm to 63 mm for snow. The corrections increase precipitation by about 3 mm - 14 mm for rain, and 10 mm - 54 mm for snow, indicating the relative increases are 11% - 54% for rain, and 33% - 100% for snow.

For Glasgow International Airport station in U.S. (Figure 3-11), the peaks of monthly measured and corrected precipitation both occur in July (95 mm and 107 mm, respectively).



The lowest measured and corrected precipitation occurs in January (5 mm and 8 mm, respectively). The measured precipitation ranges from 8 mm to 95 mm for rain, and from 5 mm to 15 mm for snow. The corrections increase precipitation by about 1 mm to 13 mm for rain, and 3 mm to 10 mm for snow, or the relative increases of 12% - 28% for rain and 47% - 70% for snow.

Overall, the precipitation measurements at Rockglen station are higher than at Glasgow International Airport station for most months. Also, the average bias-correction for Rockglen station (43%) is greater than Glasgow International Airport station (35%). Also, the bias-corrections are higher in the cold months than in the warm months for both stations. The higher correction percentage for Rockglen station (Canada) is mainly due to the higher wind speeds in the cold months.

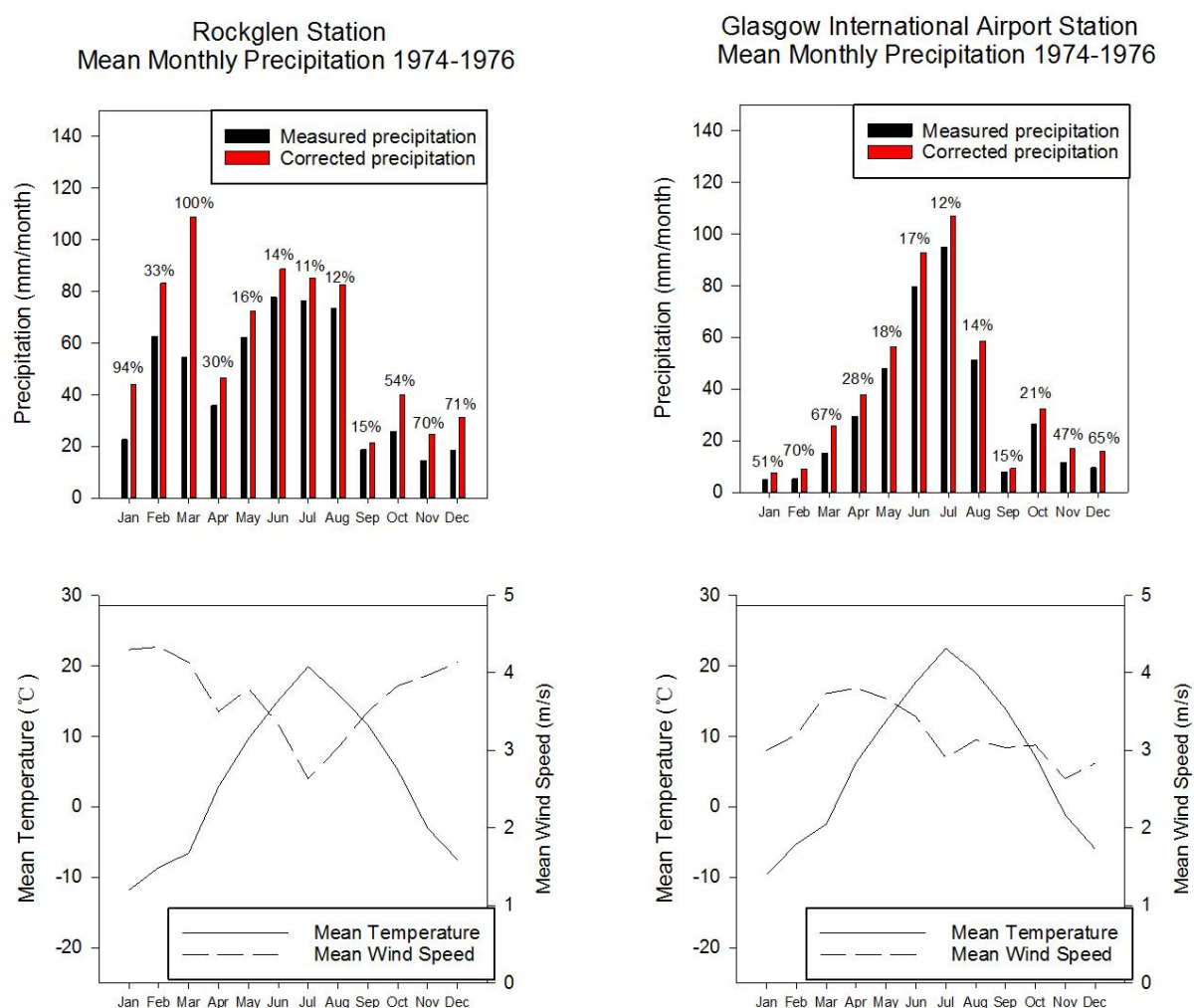


Figure 3-11. Mean monthly precipitation at Rockglen station and Glasgow International Airport station, and the corresponding mean monthly wind speed/air temperature (bottom panels) during 1974-1976. The percentage of each bar group represents the bias-correction change for that month.



### 3.3.2 Annual Precipitation

Figure 3-12 represents the annual precipitation at Rockglen station and Glasgow International Airport station during 1974-1976. The percentage of each bar group represents the bias-correction change for that year. The annual maximum and minimum precipitation (both measured and corrected precipitation) for Rockglen station occurs in 1974 and 1976, respectively; and the annual maximum and minimum precipitation (both measured and corrected precipitation) for Glasgow International Airport station occurs in 1974 and 1975, respectively. For Rockglen station, the bias-correction for each year is between 33% and 35%. However, for Glasgow International Airport station, the bias-corrections range from 20% to 25%. Therefore, the bias-corrections are higher at Rockglen station than at Glasgow International Airport station.

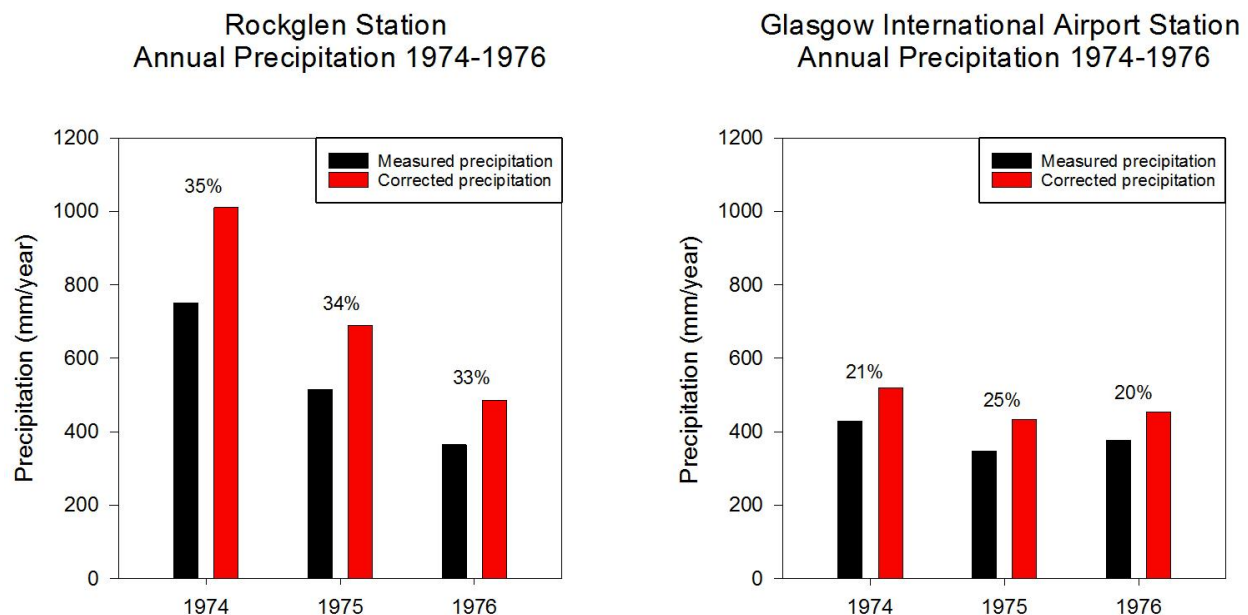


Figure 3-12. Annual measured and corrected precipitations for Rockglen station and Glasgow International Airport station during 1973-1976. The percentage of each bar group represents the bias-correction change for that year.

### 3.3.3 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-13 shows the mean annual measured and corrected precipitation for the cold and warm months at Rockglen station and Glasgow International Airport station. The percentages are the total changes from measured to corrected precipitation relative to the amount of measured precipitation. This figure displays that the total measured precipitation for Rockglen station and Glasgow International Airport station is 543 mm and 385 mm, respectively. The total corrected precipitation for Rockglen station and Glasgow International Airport station is 729 mm and 469 mm, respectively. These data display that both measured and corrected precipitation is higher at Rockglen station than at Glasgow International Airport station. Also, the overall bias-corrections from measured to corrected precipitation are 34.2% for Rockglen station, and 21.9% for Glasgow International Airport station. Within these data, the changes in the warm months are 17.9% for Rockglen station and 16.6% for Glasgow International Airport station; the changes in the cold months are 69.3% for Rockglen station and 60.2% for Glasgow International Airport station. Overall, these results indicate that the Rockglen station has higher bias-corrections than Glasgow International Airport station, especially for cold months. These changes are mainly caused by the high undercatch for snowfall measurements. Moreover, as these two stations are located 116 km apart, the precipitation difference between them may also due to the spatial distribution (Yang et al., 2003).

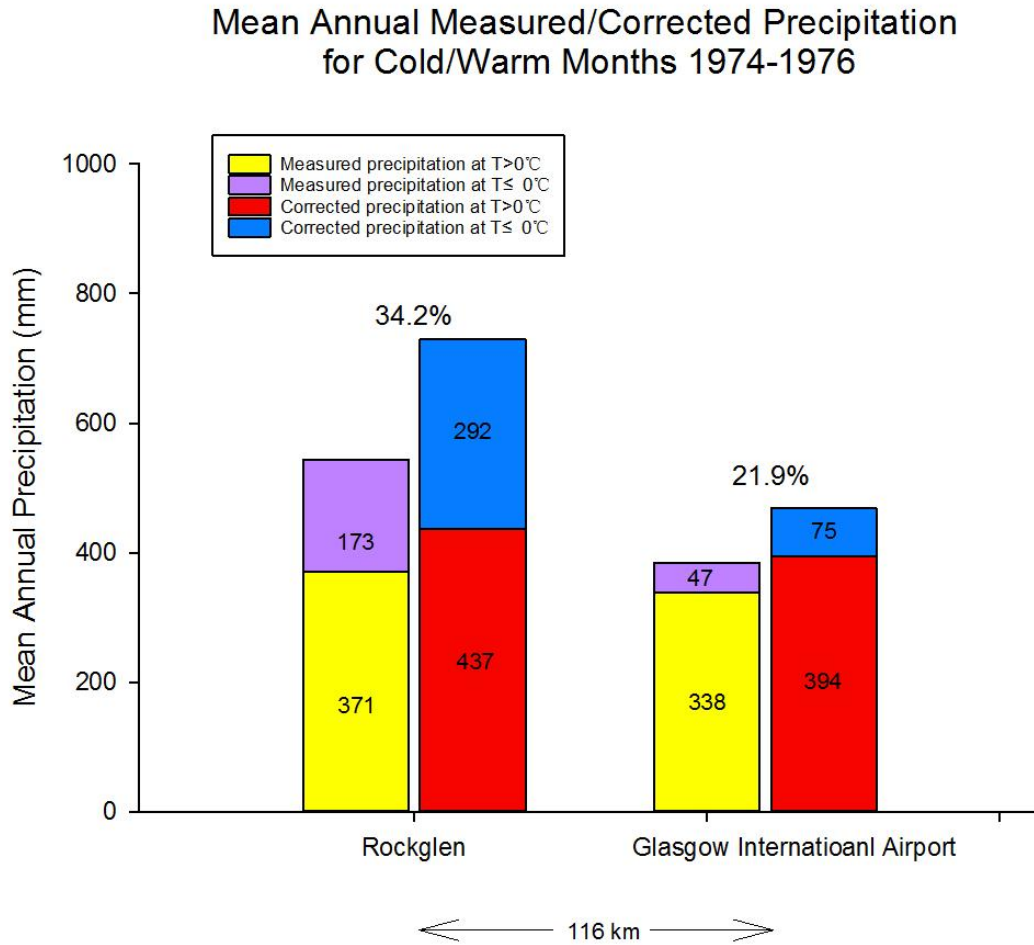


Figure 3-13. Mean annual measured and corrected precipitation for cold ( $\text{Temp} \leq 0^\circ\text{C}$ ) and warm ( $\text{Temp} > 0^\circ\text{C}$ ) months at Rockglen station and Glasgow International Airport station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the stations.

### 3.3.4 Monthly Precipitation Relationship

Figure 3-14 illustrates the scatter plots of corresponding monthly precipitation for Rockglen station and Glasgow International Airport station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. The left plot displays that the  $R^2$  for measured and corrected precipitation are 0.34 and 0.31, respectively. The  $R^2$  values suggest that the relationships between these two stations are weak in the warm months. As the regression curve for the cold months did not make sense, it did not show in the plot. Also, according to the shifts

of the regression lines, the difference between measured and corrected precipitation in the warm months is very small.

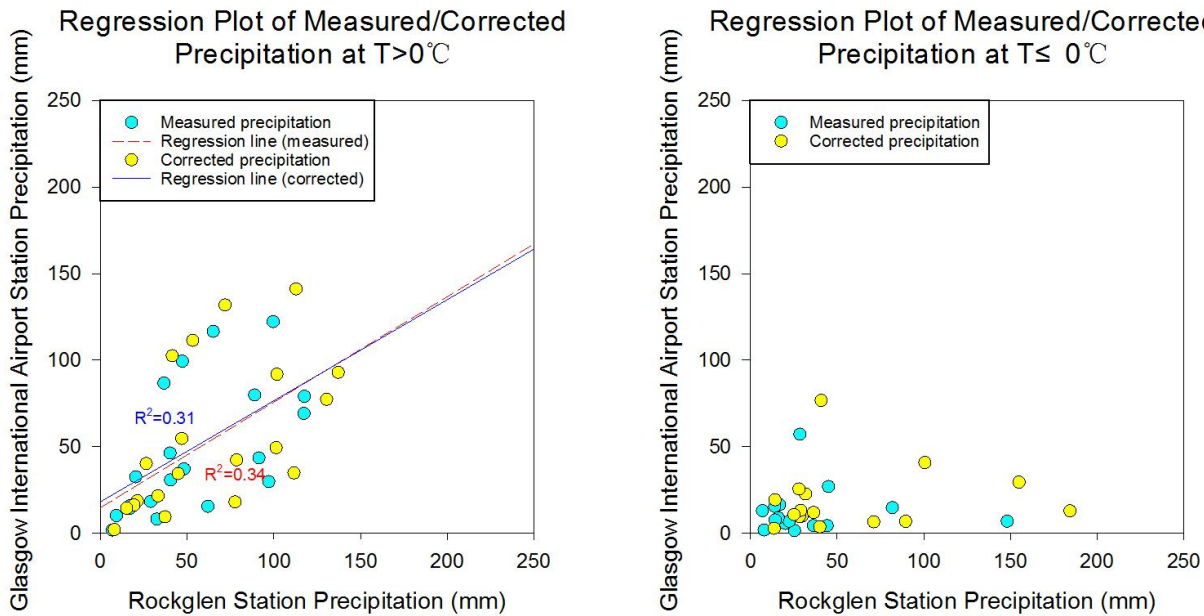


Figure 3-14. Scatter plots between Rockglen station and Glasgow International Airport station for the measured and corrected precipitation. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months.

### 3.3.5 Accumulation of Monthly Precipitation

Figure 3-15 represents the DMCs between Rockglen station (Canada) and Glasgow International Airport station (U.S.). This plot indicates that both accumulated measured and corrected precipitation is higher at Rockglen station than at Glasgow International Airport station. Also, the slopes of both curves are not constant, which mean that the relationships between the two stations for both measured and corrected precipitation are not constant over the three years. The changing slopes imply the existence of discontinuity in precipitation across the border. Figure 3-15 also displays that the slopes for both measured and corrected precipitation start increasing since February 1974. Also, this figure shows that there are many significant gaps around 1100 mm (corrected precipitation) and 1900 mm (corrected precipitation) at Rockglen station. At the end points, from the measured precipitation to corrected precipitation, the point shifts more to the right side than upward, indicating that the bias-corrections are higher at the Rockglen station than at Glasgow International Airport station. Also, at the end points, the difference of measured

precipitation between these two stations is about 475 mm; however, the difference of corrected precipitation between these two stations decreases to 780 mm. Therefore, it reveals that the observed (measured) precipitation difference underestimates the precipitation difference between the paired stations.

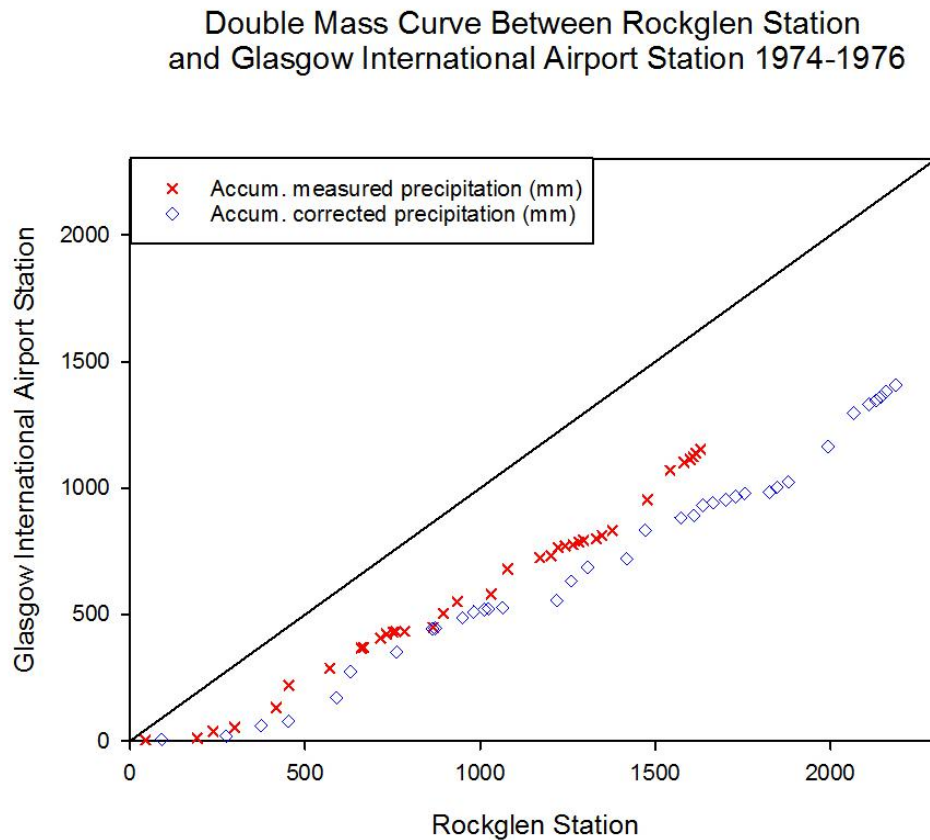


Figure 3-15. Double mass curve between Rockglen station and Glasgow International Airport station during 1974–1976.

### **3.4 Estevan Airport (CA) and Williston-Sloulin Field International Airport (U.S.) stations**

Estevan Airport station is located in Saskatchewan province in Canada. Its geographical coordinates are 49.21N, -102.96W, and its elevation is 581 m (Environment Canada, 2016). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by croplands (88%) and grasslands (12%) (Peel et al, 2007).

Williston-Sloulin Field International Airport station is located in North Dakota State in U.S. Its geographical coordinates are 48.20N, -103.65W, and its elevation is 580 m (NOAA). This station has a semi-arid steppe climate. Within 40 km of this station, the region is covered by croplands (48%), grasslands (45%), and lakes and rivers (7%) (Peel et al, 2007). This station is close to Yellowstone River and the Missouri River, Lake Sakakawea.

The original data used for this paired stations are daily and monthly measured/corrected precipitation data from 1980-1998. Moreover, the distance between these two stations is 123 km.

#### **3.4.1 Daily Precipitation**

Figure 3-16 represents the probability of daily measured and corrected precipitation at Estevan Airport and Williston-Sloulin Field International Airport stations. The plot shows that the daily precipitation amounts for both stations mainly occur between 0 and 20 mm. The peak for each curve occurs at 2 mm. The peak of measured precipitation curve is a bit lower if comparing to the peak of corrected precipitation curve at Estevan Airport station. However, the probability peak of measured precipitation curve decreases about 0.025 if comparing to the corrected precipitation curve at Williston-Sloulin Field International Airport station, and the probability of higher precipitation amount increases.

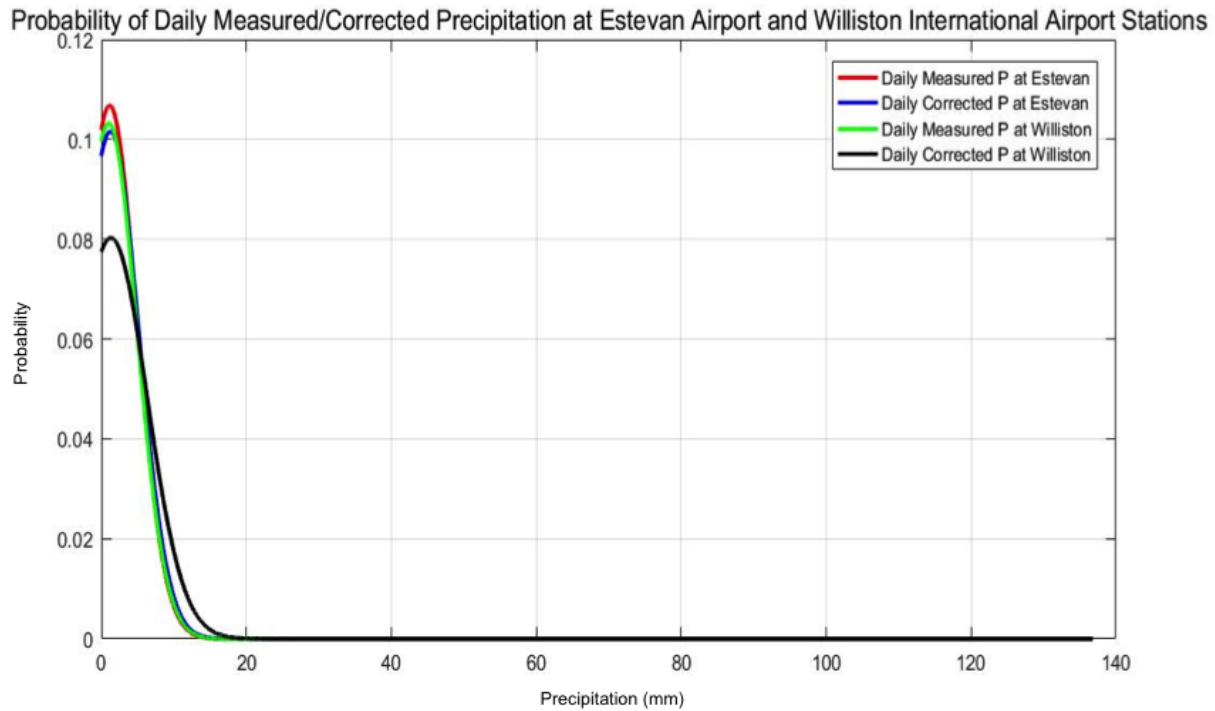


Figure 3-16. Probability density function for daily measured and corrected precipitation at Estevan Airport and Williston-Sloulin International Airport stations.

Figure 3-17 shows that the maximum daily measured and corrected precipitation of each year and their corresponding wind speed at Estevan Airport and Williston-Sloulin Field International Airport stations during 1980-1998. This figure indicates that the differences between measured and corrected precipitation for the warm and cold months at Estevan Airport are smaller than those at Williston-Sloulin International Airport, which implies the bias-corrections are smaller at Estevan Airport station than at Williston-Sloulin Field International Airport station. Besides, the bias-corrections for both stations are lower in the warm months than in the cold months. Also, for both stations, the maximum daily precipitation in the cold months is lower than those in the warm months. However, there are several years that the maximum precipitation is higher in the cold months, which are mainly due to the high wind speed in the warm months. Besides, the maximum daily precipitation during 1980-1998 at Estevan and Williston-Sloulin Field International Airport stations occurs in 1993 and 1997, respectively, and both occur during the warm months. The lowest maximum daily precipitation at Estevan and Williston-Sloulin Field International Airport stations occurs in 1986 and 1981, respectively, and both occur during the cold months.



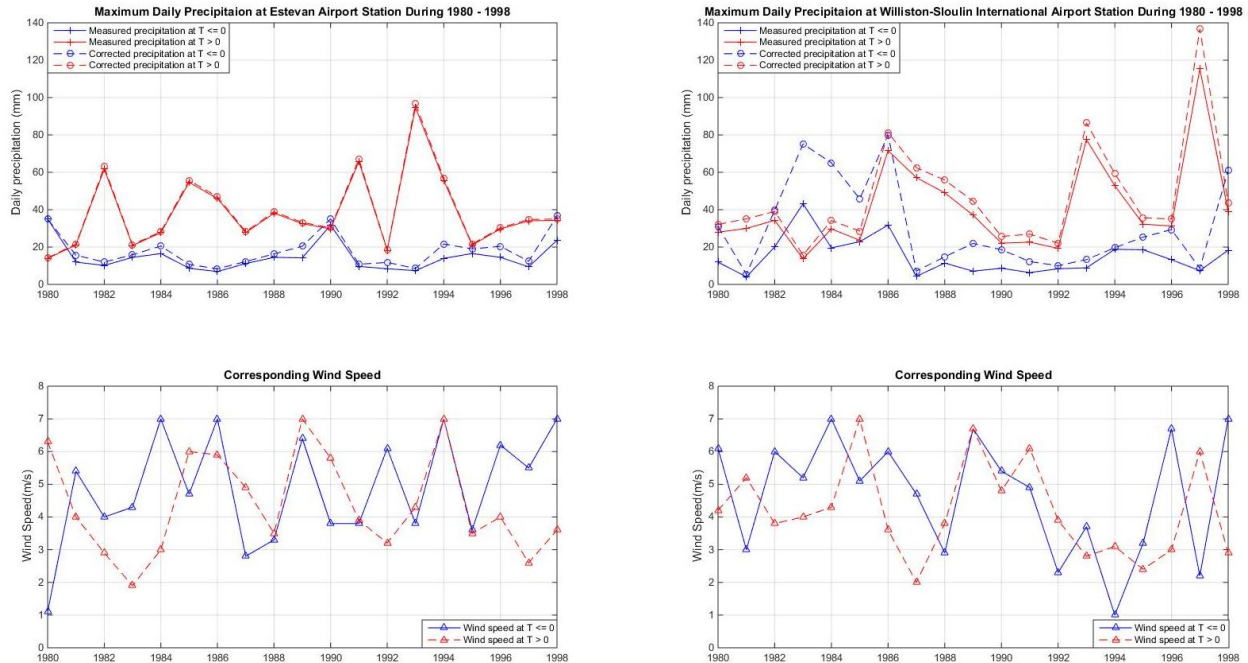


Figure 3-17. Maximum daily measured and corrected precipitation of each year and their corresponding wind speed at Estevan Airport and Williston-Sloulin International Airport stations during 1980 – 1998.

### 3.4.2 Monthly Precipitation

Figure 3-18 shows the mean monthly precipitation, wind speed and air temperature at Estevan Airport station (Canada) and Williston-Sloulin Field International Airport station (U.S.) during 1980-1998. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. According to temperature, the cold months for these two stations are from November to March, and the warm months are from April to October. The upper two plots display that the mean monthly precipitation distributions of these two stations are similar. Such as the highest monthly precipitation for both stations occurs in July, which corresponds to the low wind speed and high temperature. Also, both measured and corrected precipitation is higher in the warm months than the cold months, which corresponds to the low wind speed and high temperature.

For Estevan Airport station in Canada (Figure 3-18), the peaks of monthly measured and corrected precipitation both occur in July (73 mm and 75 mm, respectively), which correspond to the high temperature and low wind speed. The lowest measured and corrected precipitation occurs in December (16 mm and 19 mm, respectively), corresponding to the relatively high wind

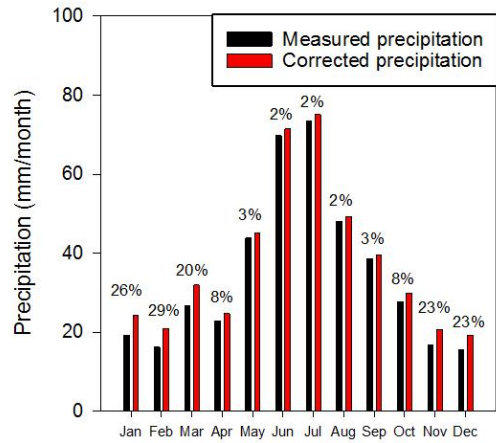


speed and low temperature. The measured precipitation ranges from 23 mm to 70 mm for rain, and from 16 mm to 27 mm for snow. The corrections increase precipitation by about 1 mm - 2mm for rain, and 4 mm - 5 mm for snow, indicating that the relative increases are 2% - 8% for rain, and 20% - 29% for snow.

For Williston-Sloulin Field International Airport station in U.S. (Figure 3-18), the peaks of monthly measured and corrected precipitation both occur in July (65 mm and 73 mm, respectively), corresponding to the high temperature and low wind speed; the lowest measured and corrected precipitation occurs in February (9 mm and 19 mm, respectively). The measured precipitation ranges from 24 mm to 65 mm for rain, and from 9 mm to 21 mm for snow. The bias-corrections increase precipitation by about 5 mm - 12 mm for rain, and 10 mm - 13 mm for snow, or the relative increases of 12% - 49% for rain, and 59% - 107% for snow.

Overall, Estevan Airport station has higher measured precipitation than Williston-Sloulin Field International Airport station for most months; however, after bias-correction, the corrected precipitation at Williston-Sloulin Field International Airport station becomes greater than Estevan Airport station for some months. Also, the average bias-correction for Estevan Airport station (12%) is lower than Williston-Sloulin Field International Airport station (40%). Besides, for both stations, the bias-corrections are higher in the cold months than in the warm months. The lower correction percentage for Estevan Airport station (Canada) is mainly due to the lower undercatch of the Nipher snow gauge, and also the lower wind speeds in the cold months.

Estevan Airport Station  
Mean Monthly Precipitation 1980-1998



Williston-Sloulin Field International Airport Station  
Mean Monthly Precipitation 1980-1998

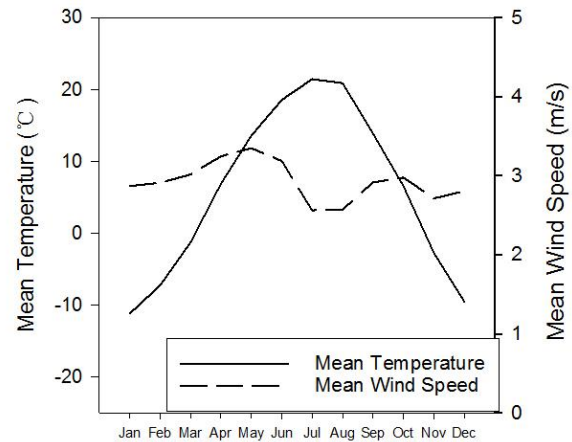
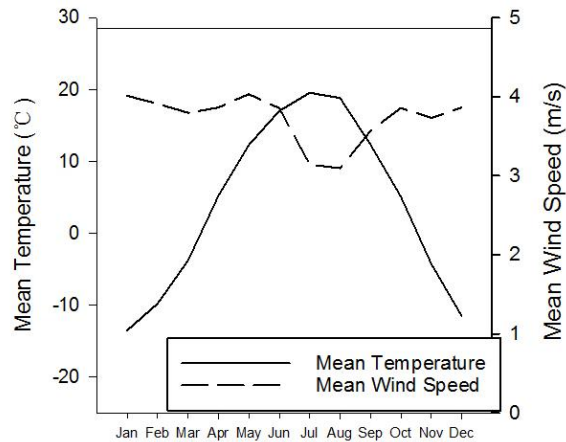
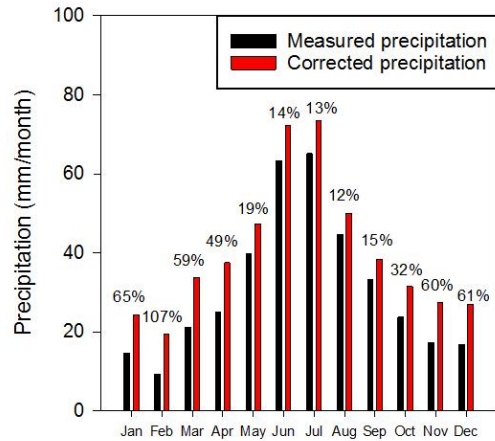


Figure 3-18. Mean monthly precipitation at Estevan Airport station (Canada) and Williston-Sloulin Field International Airport station (U.S.) (upper panels), and the corresponding mean monthly wind speed/air temperature (bottom panels) during 1980–1998. The percentage on each bar group represents the bias-correction change for that month.

Figure 3-19 and Figure 3-20 represent the monthly precipitation of each year in February and in July at Estevan Airport station (Canada) and Williston-Sloulin Field International Airport station (U.S.). Both figures show that the bias-corrections are lower at Estevan Airport station than at Williston-Sloulin International Airport station. Also, for both stations, the bias-corrections are higher in February than in July, which is mainly due to the high wind speed in the cold months. Besides, the measured precipitation in both February and July is higher at Estevan Airport station than at Williston-Sloulin International Airport station for most years. However, there is no obvious trend for precipitation in February or in July over the nineteen years.

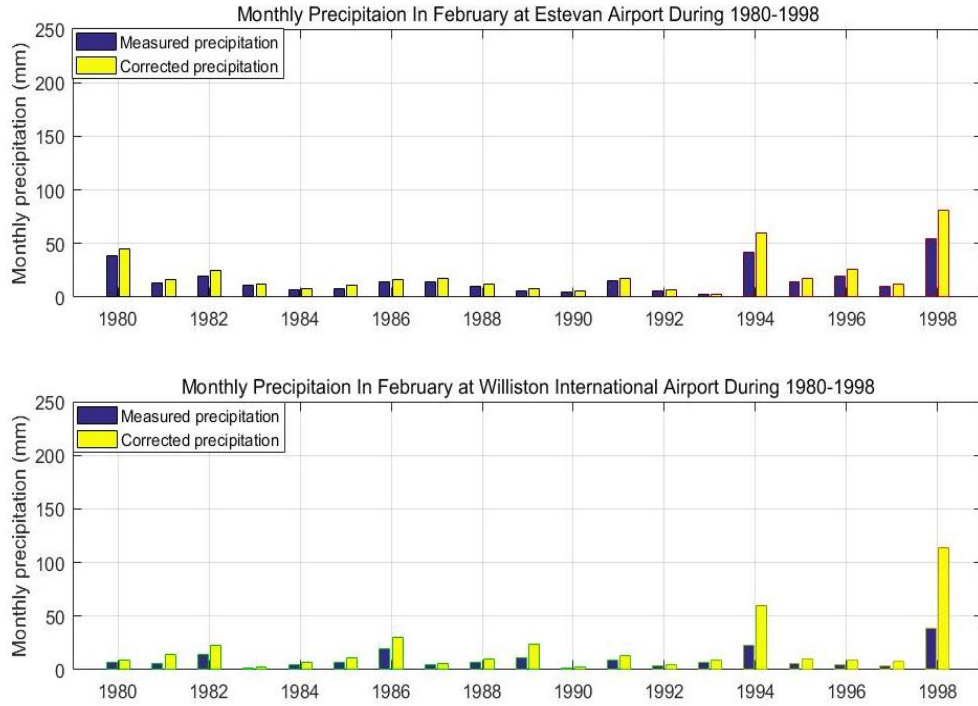


Figure 3-19. Monthly precipitation of each year in February at Estevan Airport station (Canada, upper plot) and Williston-Sloulin Field International Airport station (U.S., bottom plot).

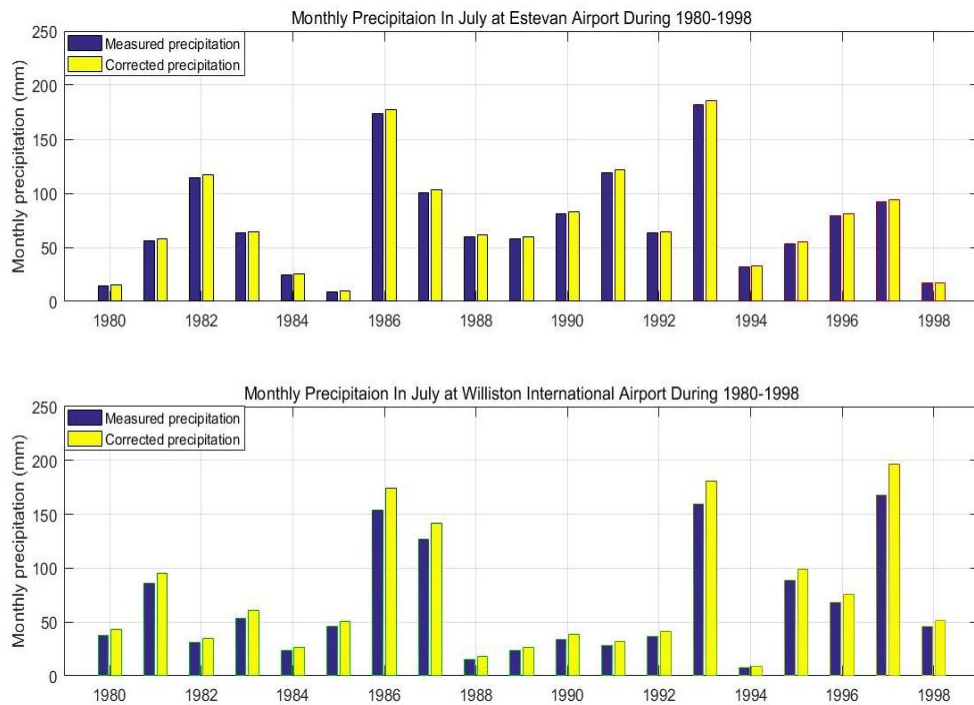
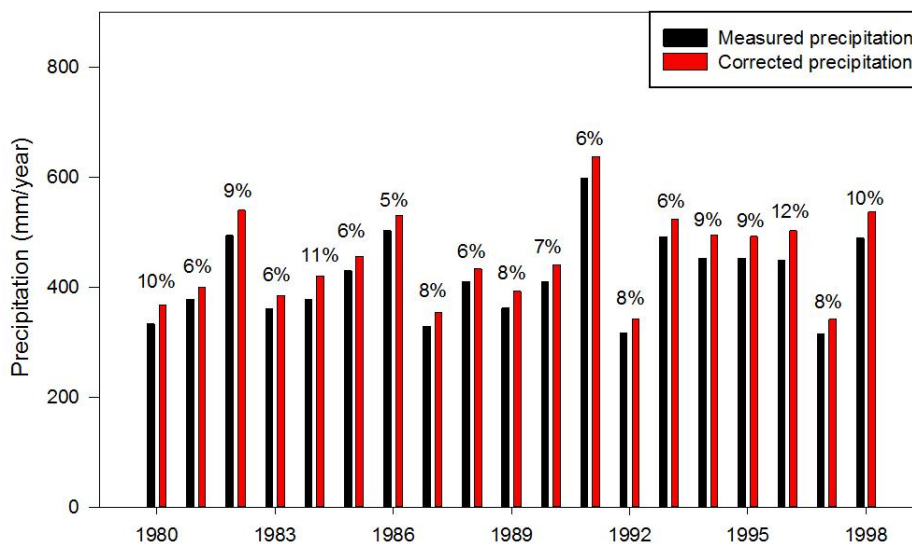


Figure 3-20. Monthly precipitation of each year in July at Estevan Airport station (Canada, upper plot) and Williston-Sloulin Field International Airport station (U.S., bottom plot).

### Estevan Airport Station Annual Precipitation 1980-1998



### Williston-Sloulin Field International Airport Station Annual Precipitation 1980-1998

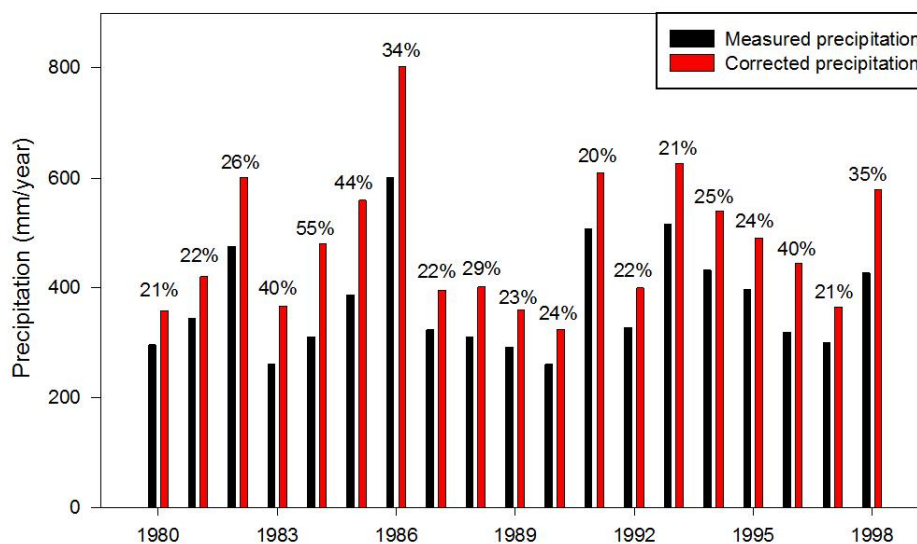


Figure 3-21. Annual precipitation at Estevan Airport station (Canada, upper plot) and Williston-Sloulin Field International Airport station (U.S., bottom plot) during 1980-1998. The percentage of each bar group represents the bias-correction change for that year.

### 3.4.4 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-22 shows the mean annual measured and corrected precipitation for the cold and warm months at Estevan Airport and Williston-Sloulin Field International Airport station. The percentages are the total changes from measured to corrected precipitation relative to the amount of measured precipitation. This figure displays that total measured precipitation for Estevan Airport and Williston-Sloulin Field International Airport station is 419 mm and 375 mm, respectively. Moreover, the total corrected precipitation for Estevan Airport and Williston-Sloulin Field International Airport station is 452 mm and 483 mm, respectively. These data display that the measured precipitation is higher at Estevan Airport Station than at Williston-Sloulin Field International Airport station; however, after bias-correction, the precipitation at Williston-Sloulin Field International Airport station is higher than Estevan Airport station, which indicates the gradient's direction change due to bias-corrections. Also, the overall bias-corrections from measured to corrected precipitation are 8.0% for Estevan Airport station and 28.8% for Williston-Sloulin Field International Airport station. Within these data, the changes in the warm months are 3.4% for Estevan Airport station and 18.8% for Williston-Sloulin Field International Airport station; the changes in the cold months are 23.7% for Estevan Airport station and 66.3% for Williston-Sloulin Field International Airport station. Overall, these results indicate that the Williston-Sloulin Field International Airport station has higher bias-corrections than Estevan Airport station, especially for cold months. These changes are mainly due to high undercatch for snowfall measurements. Moreover, as these two stations are located 123 km apart, the precipitation difference between them may also due to the spatial distribution (Yang et al., 2003).

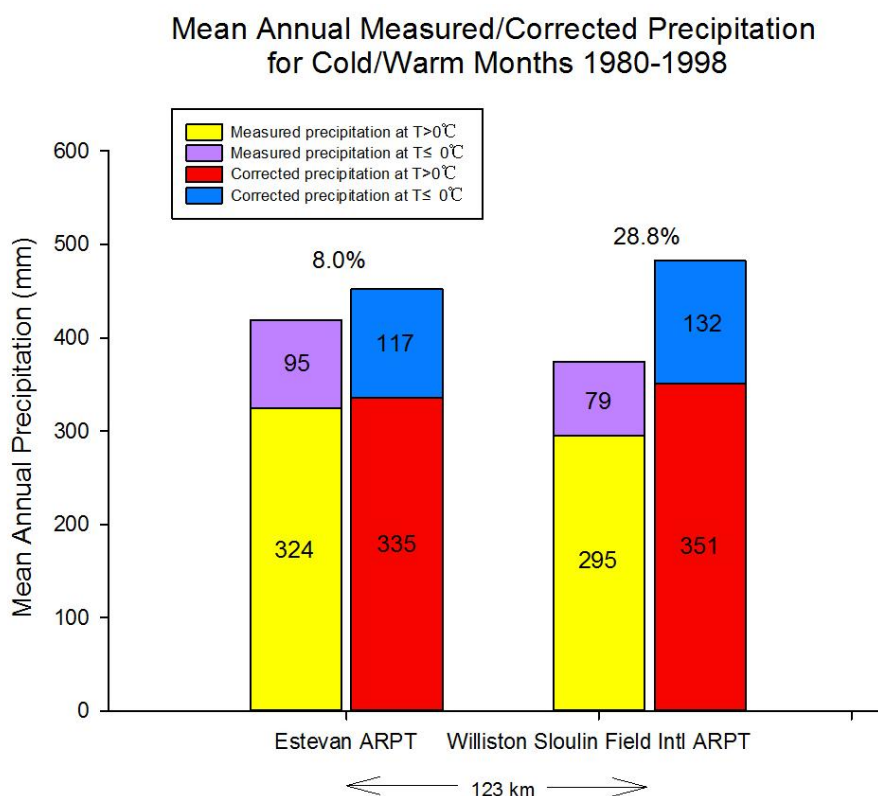


Figure 3-22. Mean annual measured and corrected precipitation for cold ( $T \leq 0^{\circ}\text{C}$ ) and warm ( $T > 0^{\circ}\text{C}$ ) months at Estevan Airport Station and Williston-Sloulin Field International Airport station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the stations.

### 3.4.5 Monthly Precipitation Relationship

Figure 3-23 illustrates the scatter plots of corresponding monthly precipitation for Estevan Airport station and Williston-Sloulin Field International Airport station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. The left plot displays that the  $R^2$  for measured and corrected precipitation are 0.49 and 0.52, respectively. The right plot displays that the  $R^2$  for measured and corrected precipitation are 0.46 and 0.42, respectively. The  $R^2$  values suggest that the relationships between these two stations are weak in both warm and cold months; however, the relationships are relatively stronger in the warm months than in the cold months, for both measured and corrected data. Also, according to the shifts of the regression lines, the difference between measured and corrected precipitation is higher in the cold months than in the warm months. The difference is mainly caused by the high bias-correction at Williston-Sloulin Field International Airport station.

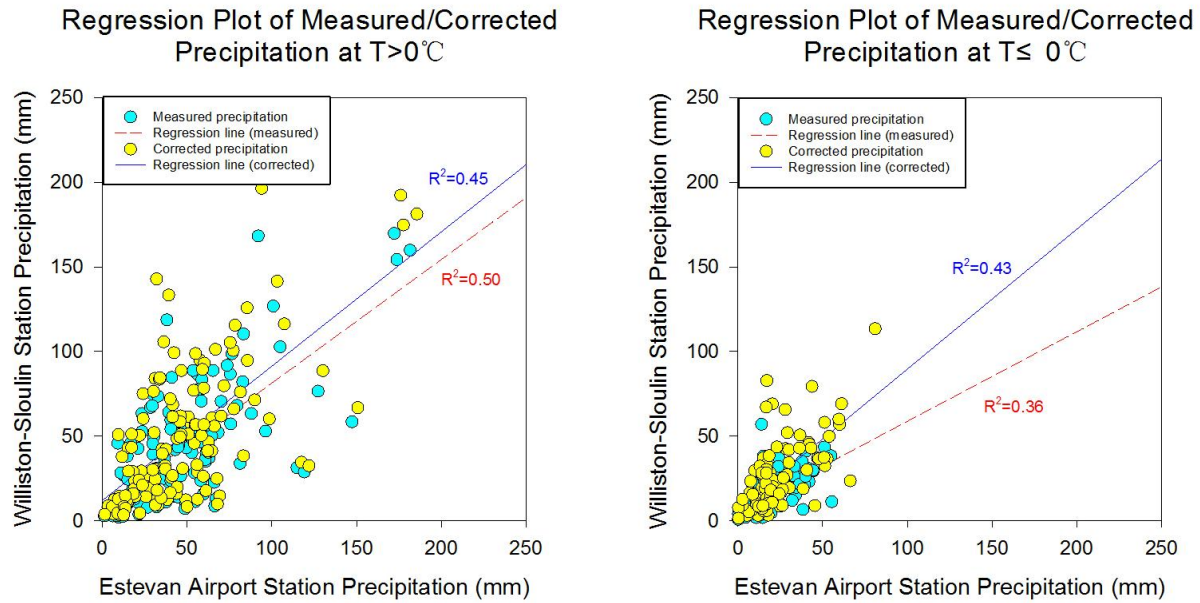


Figure 3-23. Scatter plots of corresponding monthly precipitation for Estevan Airport station and Williston-Sloulin Field International Airport station. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold month.

### 3.4.6 Accumulation of Monthly Precipitation

Figure 3-24 represents the DMCs between Estevan Airport station (Canada) and Williston-Sloulin Field International Airport station (U.S.). This plot indicates that the accumulated measured precipitation is higher at Estevan Airport station, but the accumulated corrected precipitation is higher at Williston-Sloulin Field International Airport station, which implies the gradient's direction changed due to bias-correction. Also, both curves in this figure have nearly constant slopes, indicating the relationships between the two stations for both measured and corrected precipitation are constant over the nineteen years. The constant slopes imply the precipitation measurements across the border are continuous. At the end points, from the measured precipitation to corrected precipitation, the point shifts more upward than to the right side, implying that bias-corrections are higher at the Williston-Sloulin Field International Airport station than at Estevan Airport station. Moreover, at the end points, the difference of measured precipitation between these two stations is about 900 mm; however, the difference of corrected precipitation between these two stations decreases to 600 mm. Therefore, it reveals that the observed (measured) precipitation difference overestimates the precipitation difference between the paired stations.



Double Mass Curve Between Estevan Airport Station  
and Williston-Sloulin Field Intl' Airport Station 1980-1998

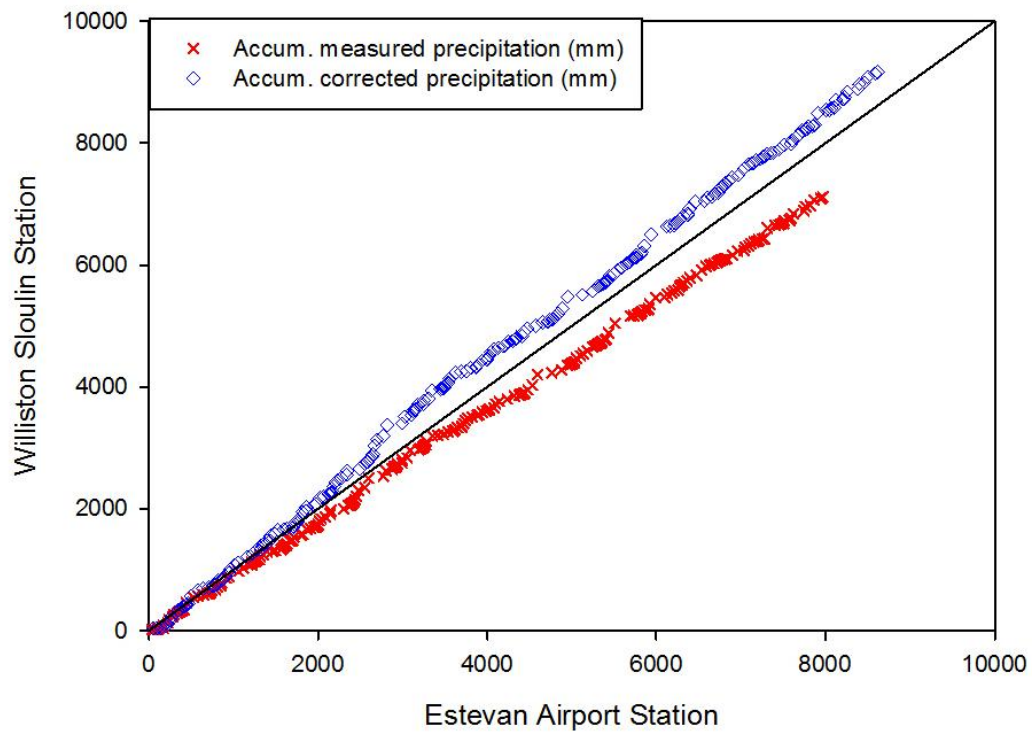


Figure 3-24. Double mass curve between Estevan Airport station and Williston-Sloulin Field International Airport station during 1980-1998.



### **3.5 Sault Ste Marie (CA) and Pellston Emmet County (U.S.) stations**

Sault Ste Marie station is located in Ontario province in Canada. Its geographical coordinates are 46.48N, -84.51W, and its elevation is 192 m (Environment Canada, 2016). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by forests (42%), oceans and seas (26%), croplands (26%), and lakes and rivers (5%) (Peel et al, 2007).

Pellston Emmet County station is located in Michigan State in U.S. Its geographical coordinates are 45.57N, -84.79W, and its elevation is 217 m (NOAA). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by forests (43%), croplands (30%), oceans and seas (18%), and lakes and rivers (7%) (Peel et al, 2007).

The original data used for this paired stations are monthly measured and corrected precipitation data from 1997-1998. Moreover, the distance between these two stations is 105km.

#### **3.5.1 Monthly Precipitation**

Figure 3-25 illustrates the mean monthly measured and corrected precipitation at Sault Ste Marie station and Pellston Emmet County station during 1997-1998. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. Based on temperature, the cold months for these two stations are from December to March, and the warm months are from April to November. The upper two plots show that the mean monthly precipitation distributions of these two stations are different. For instance, the maximum and minimum measured precipitation at Sault Ste Marie station occurs in September and February, respectively; however, the highest and lowest measured precipitation at Pellston Emmet County station occurs in January and June, respectively.

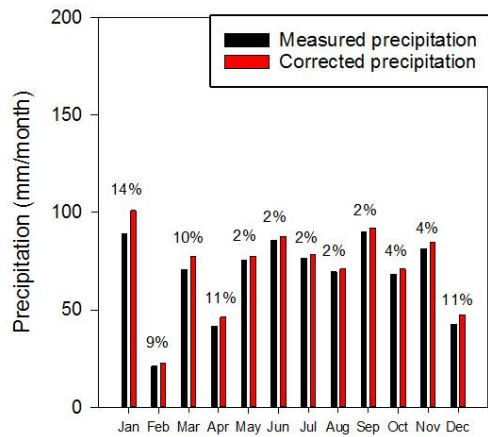
For Sault Ste Marie station in Canada (Figure 3-25), the precipitation varies over months. The peaks of monthly measured and corrected precipitation occur in September (90 mm) and January (101 mm), respectively. The lowest measured and corrected precipitation both occur in February (35 mm and 90 mm, respectively). The measured precipitation ranges from 42 mm to 90 mm for rain, and from 21 mm to 89 mm for snow. The corrections increase

precipitation by about 2 mm - 5 mm for rain and 2 mm - 12 mm for snow, which mean that the relative increases are 2% - 11% for rain, and 9% - 14% for snow.

For Pellston Emmet County station in U.S. (Figure 3-25), the precipitation varies over months as well. The peaks of monthly measured and corrected precipitation both occur in January (94 mm and 141 mm, respectively). The lowest measured and corrected precipitation both occur in June (31 mm and 36 mm, respectively). The measured precipitation ranges from 31 mm to 84 mm for rain and from 35 mm to 94 mm for snow. The corrections increase precipitation by about 4 mm - 14 mm for rain, and 15 mm - 47 mm for snow, or the relative increases of 8% - 21% for rain, and 38% - 50% for snow.

Overall, Pellston Emmet County station has higher precipitation (both measured and corrected) than Sault Ste Marie station for most months. Moreover, for Sault Ste Marie station, the measured and corrected precipitation is higher in the warm months than in the cold months; however, for Pellston Emmet County station, the measured and corrected precipitation is higher in the cold months than in the warm months. Also, the precipitation ranks for both stations changed due bias-corrections. Besides, the average bias-correction for Sault Ste Marie station (6%) is lower than Pellston Emmet County station (24%). The lower correction percentage for Sault Ste Marie station (Canada) is mainly due to the lower undercatch of the Nipher snow gauge, and also the lower wind speeds in the cold months.

Sault Ste Marie Station  
Mean Monthly Precipitation 1997-1998



Pellston Emmet County Station  
Mean Monthly Precipitation 1997-1998

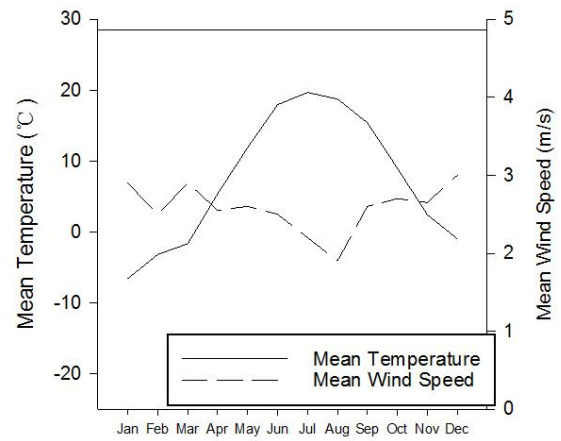
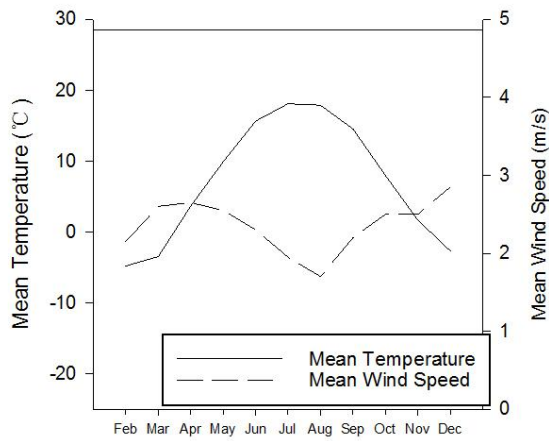
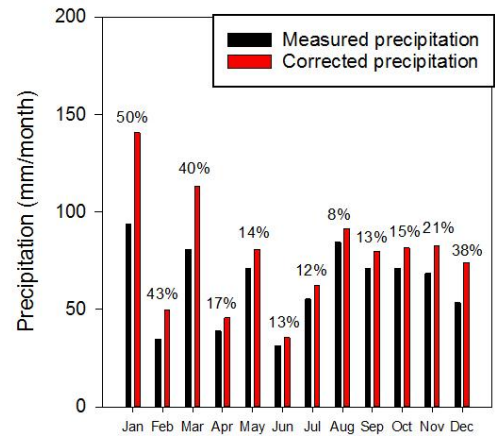


Figure 3-25. Sault Ste Marie station and Pellston Emmet County station mean monthly precipitation and corresponding mean monthly wind speed/air temperature (bottom panels) during 1997-1998. The percentage of each bar group represents the bias-correction change for that month.

### 3.5.2 Annual Precipitation

Figure 3-26 represents the annual measured and corrected precipitation for Sault Ste Marie station and Pellston Emmet County station during 1997-1998. The percentage of each bar group represents the bias-correction change for that year. Both these two stations have higher precipitation (both measured and corrected precipitation) in 1997 than in 1998. Besides, Sault Ste Marie Station has higher measured precipitation for both years (798 mm and 727 mm, respectively); however, after bias-corrections, Pellston Emmet County Station has higher corrected precipitation for both years (936 mm and 902 mm, respectively). The results imply the gradient's direction changed due to bias-correction. Besides, the average bias-corrections for Sault Ste Marie station and Pellston Emmet County station for these two years are 6% and 23%, respectively, which reveals that Pellston Emmet County station has much higher bias-corrections than Sault Ste Marie station.

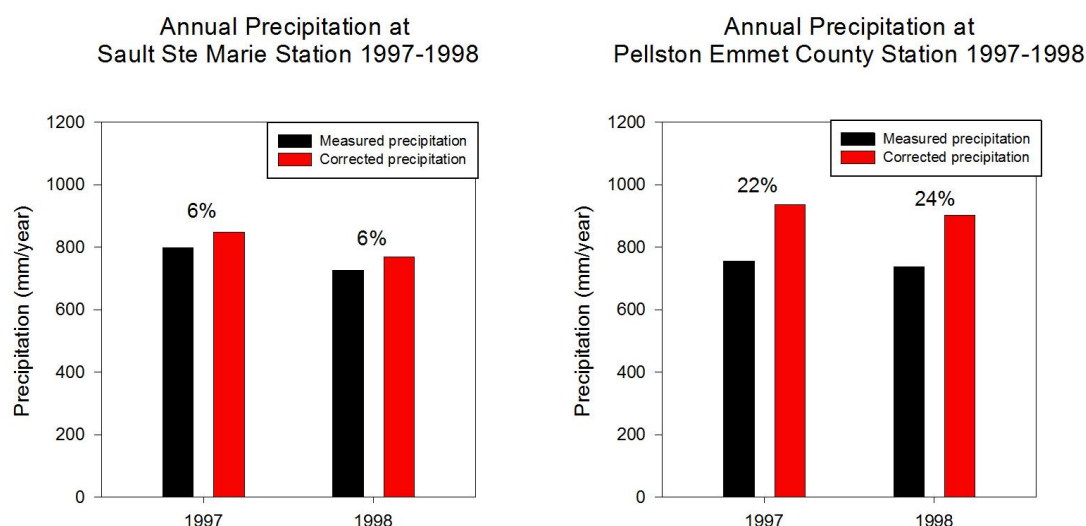


Figure 3-26. Annual measured and corrected precipitations for Sault Ste Marie station and Pellston Emmet County station during 1997-1998. The percentage of each bar group represents the bias-correction change for that year.

### 3.5.3 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-27 shows the mean annual measured and corrected precipitation for the cold and warm months at Sault Ste Marie station and Pellston Emmet County station. The percentages are the changes from measured precipitation to corrected precipitation relative to the amount of measured precipitation. This figure displays that the total measured precipitation for Sault Ste Marie station and Pellston Emmet County station is 813 mm and 755 mm, respectively. Moreover, the total corrected precipitation for Sault Ste Marie station and Pellston Emmet County station is 858 mm and 871mm, respectively. These data show that Sault Ste Marie

station has higher measured precipitation, but after bias-corrections, Pellston Emmet County station has higher precipitation. The results imply the gradient's direction change due to bias-correction. Also, the overall bias-corrections are 5.6% for Sault Ste Marie station and 15.4% for Pellston Emmet County station. Within these data, the changes in the warm months are 3.3% for Sault Ste Marie station and 19.6% for Pellston Emmet County station; and the changes in the cold months are 11.5% for Sault Ste Marie station and 7.6% for Pellston Emmet County station. Overall, these results indicate that Sault Ste Marie Sanderson station has higher bias-corrections than Sault Ste Marie station, but remarkable, the changes are mainly due to the high undercatch for rainfall measurements. Moreover, as these two stations are located 105 km apart, the precipitation difference between them may also due to the spatial distribution (Yang et al., 2003).

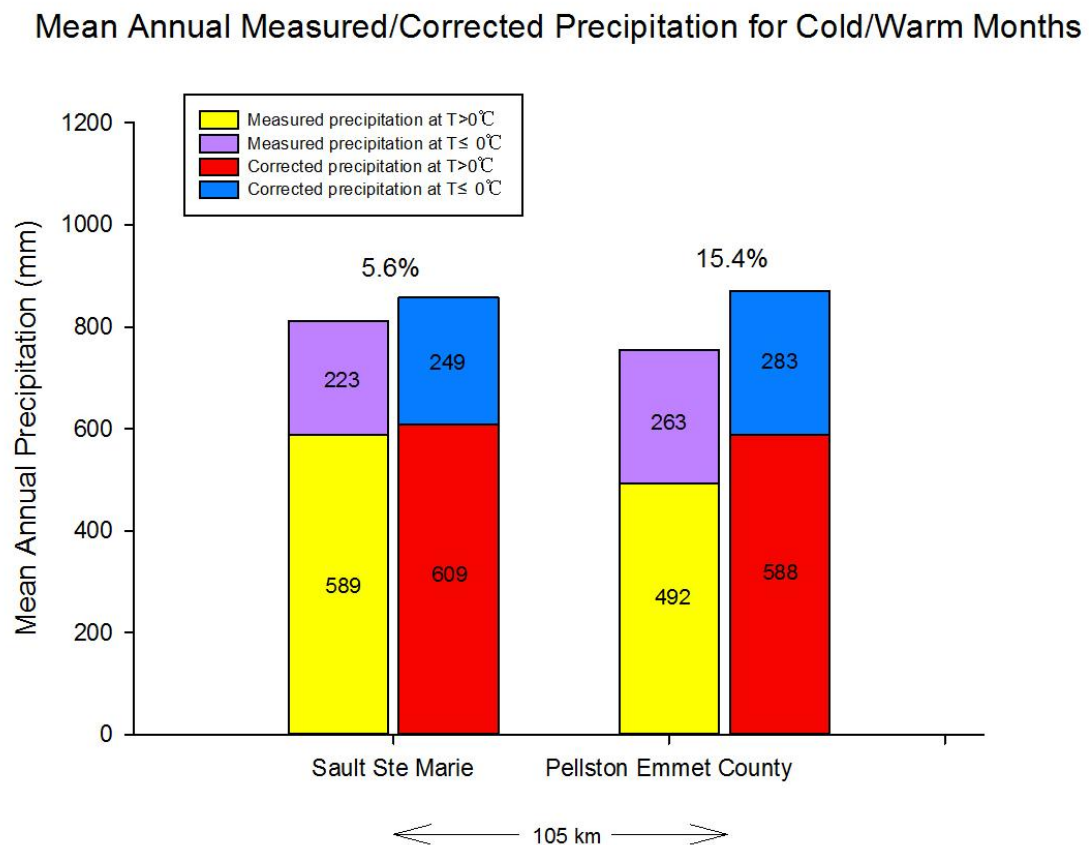


Figure 3-27. Mean annual measured and corrected precipitation for cold ( $\text{Temp} \leq 0^{\circ}\text{C}$ ) and warm ( $\text{Temp} > 0^{\circ}\text{C}$ ) months at Sault Ste Marie station and Pellston Emmet County station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the two stations.

### 3.5.4 Monthly Precipitation Relationship

Figure 3-28 shows the scatter plots between Sault Ste Marie station and Pellston Emmet County station for the measured and corrected precipitation. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. As the regression line for the warm months did not make sense, it did not show in the plot. The right plot displays that the  $R^2$  for measured and corrected precipitation are 0.56 and 0.61, respectively. The results indicate that the relationships between two stations are strong in the cold months. Also, according to the large shifts of the regression lines in the right plot, it indicates a large difference between measured and corrected precipitation in the cold months. The difference is mainly due to the high bias-corrections at Pellston Emmet County station.

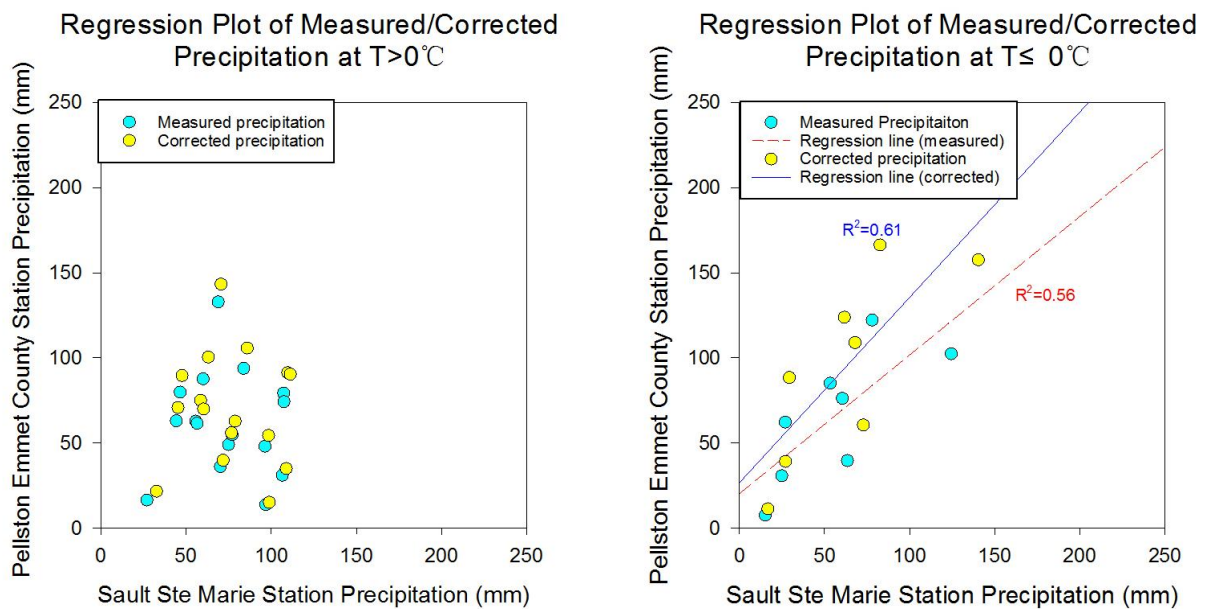


Figure 3-28. Scatter plots between Sault Ste Marie station and Pellston Emmet County station for the measured and corrected precipitation. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months.

### 3.5.5 Accumulation of Monthly Precipitation

Figure 3-29 represents the DMCs between Sault Ste Marie station and Pellston Emmet County station during 1997-1998. This plot indicates that the overall accumulated measured precipitation is higher at Pellston Emmet County station, but the accumulated corrected precipitation is higher at Sault Ste Marie station, implying the gradient's direction changed due to bias-correction. Also, the slopes of both curves changed, indicating that the relationships between the two stations for both measured and corrected precipitation are not constant over the two years. The changing slopes imply the existence of discontinuity in precipitation across the border. At the end points, from the measured precipitation to corrected precipitation, the point shifts more upward than to the right side, indicating that the bias-corrections are higher at the Pellston Emmet County station than at Sault Ste Marie station. Besides, at the end points, the difference of measured precipitation between these two stations is about 115 mm; however, the difference of corrected precipitation between these two stations increases to 161 mm. Therefore, it reveals that the measured precipitation underestimates the precipitation difference between the paired stations.

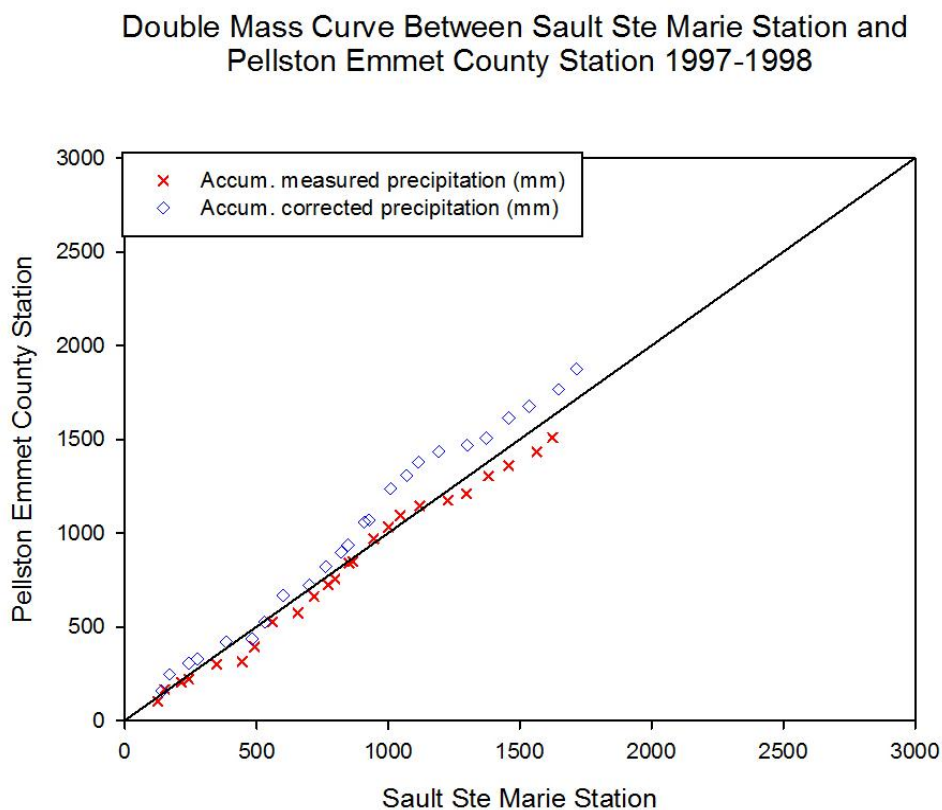


Figure 3-29. Double mass curve between Sault Ste Marie station and Pellston Emmet County station from 1997-1998.

### **3.6 Fredericton Airport (CA) and Houlton International Airport (U.S.) stations**

Fredericton Airport station is located in New Brunswick province in Canada. Its geographical coordinates are 45.88N, -66.53W, and its elevation is 20 m (Environment Canada, 2016). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by forests (92%), lakes and rivers (4%), and grasslands (4%). This station is close to Saint John River and Nashwaak River (Peel et al, 2007).

Houlton International Airport station is located in Maine state in U.S. Its geographical coordinates are 46.12N, -67.79W, and its elevation is 150 m (NOAA). This station has a humid continental climate with warm summers and no dry season. Within 40 km of this station, the region is covered by forests (85%) and grasslands (13%). This station is close to Meduxnekeag River (Peel et al, 2007).

The original data used for this paired stations are daily and monthly measured/corrected precipitation data from 2000-2007. Moreover, the distance between these two stations is 102km.

#### **3.6.1 Daily Precipitation**

Figure 3-30 represents the probability of daily measured and corrected precipitation at Fredericton Airport and Houlton International Airport stations. The plot shows that daily precipitation amounts for both stations mainly occur between 0 and 30 mm. The peak for each curve occurs around 3 mm. The peak of measured precipitation curve is a bit lower if comparing to the peak of corrected precipitation curve. However, the probability peak of measured precipitation curve decreases about 0.01 if comparing to the corrected precipitation curve at Houlton International Airport, and the probability of higher precipitation amount increases.



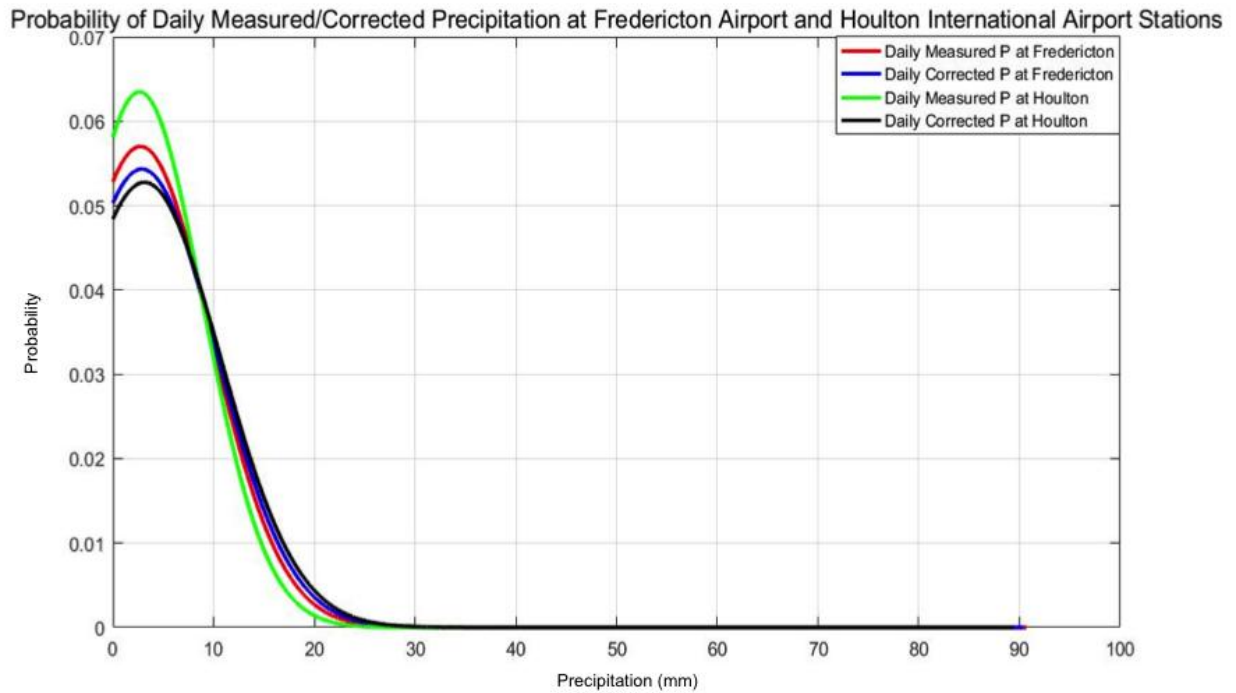


Figure 3-30. Probability density function for daily measured and corrected precipitation at Fredericton Airport and Houlton International Airport stations.

Figure 3-31 shows the maximum daily measured and corrected precipitation of each year and their corresponding wind speed at Fredericton Airport and Houlton International Airport stations during 2000-2007. This figure indicates that the differences between measured and corrected precipitation in both warm and cold months are small for Fredericton Airport station; however, the differences in the warm months are smaller than those in the cold months for Houlton International Airport station. The results imply that the bias-corrections are smaller at Fredericton Airport station than at Houlton International Airport station; also, the bias-corrections are smaller in the warm months than in the cold months. Besides, for both stations, the maximum daily precipitation in the cold months is lower than those in the warm months for most years. However, there are several years that the maximum precipitation is higher in the cold months, which is mainly due to the higher wind speed in the warm months. Also, the maximum daily corrected precipitation during 2000-2007 at Fredericton Airport and Houlton International Airport stations occur in 2004 and 2006, respectively, and both occur during warm months. The lowest maximum daily corrected precipitation at Fredericton Airport and Houlton International Airport stations occurs in 2006 and 2001, respectively, and they occur in the warm and cold months, respectively.

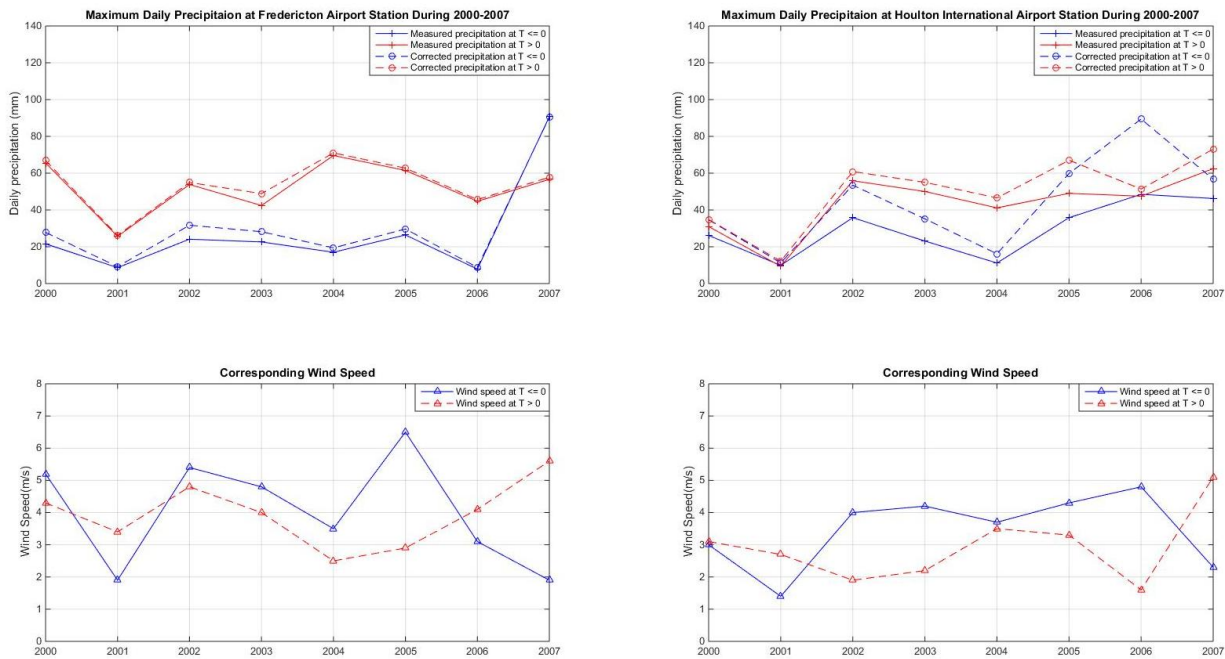


Figure 3-31. Maximum daily measured and corrected precipitation of each year and their corresponding wind speed at Fredericton Airport and Houlton International Airport stations during 2000 – 2007.

### 3.6.2 Monthly Precipitation

Figure 3-32 illustrates the mean monthly measured and corrected precipitation at Fredericton Airport station and Houlton International Airport station during 2000-2007. The upper panels are their mean monthly precipitation distributions, and the bottom panels are their corresponding mean monthly wind speed and air temperature. The percentage of each bar group represents the bias-correction change for that month. Based on temperature, the cold months for these two stations are from December to March, and the warm months are from April to November.

For Fredericton Airport station in Canada (Figure 3-32), the precipitation is steady from month to month. The peaks of monthly measured and corrected precipitation both occur in November (107 mm and 112 mm, respectively). The lowest measured and corrected precipitation both occur in February (53 mm and 60 mm, respectively). The measured precipitation ranges from 67 mm to 104 mm for rain, and from 53 mm to 81 mm for snow. The corrections increase precipitation by about 2 mm - 6 mm for rain and 7 mm - 9 mm for snow, which mean that the relative increases are 2%- 6% for rain, and 9% - 14% for snow.

For Houlton International Airport station in U.S. (Figure 3-32), the precipitation varies over months. The highest monthly measured and corrected precipitation occurs in July and November (113 mm and 132 mm, respectively). The lowest measured and corrected

precipitation both occur in February (36 mm and 54 mm, respectively). The measured precipitation ranges from 73 mm to 113 mm for rain, and from 36 mm to 73 mm for snow. The corrections increase precipitation by about 7 mm - 22 mm for rain, and 18 mm - 23 mm for snow, or the relative increases of 9% - 21% for rain, and 31% - 52% for snow.

Overall, Fredericton Airport station has higher measured precipitation, but Houlton International Airport station has higher corrected precipitation for most months. Moreover, for both stations, both measured and corrected precipitation is higher in the warm months than in the cold months. Besides, the precipitation at Fredericton Airport station is more even than at Houlton International Airport station through the year. Also, the average bias-corrections for Fredericton Airport station (6%) is lower than Houlton International Airport station (22%). The lower bias-correction percentage for Fredericton Airport station (Canada) is mainly due to the lower undercatch of the Nipher snow gauge, as well as the lower wind speeds in the cold months.

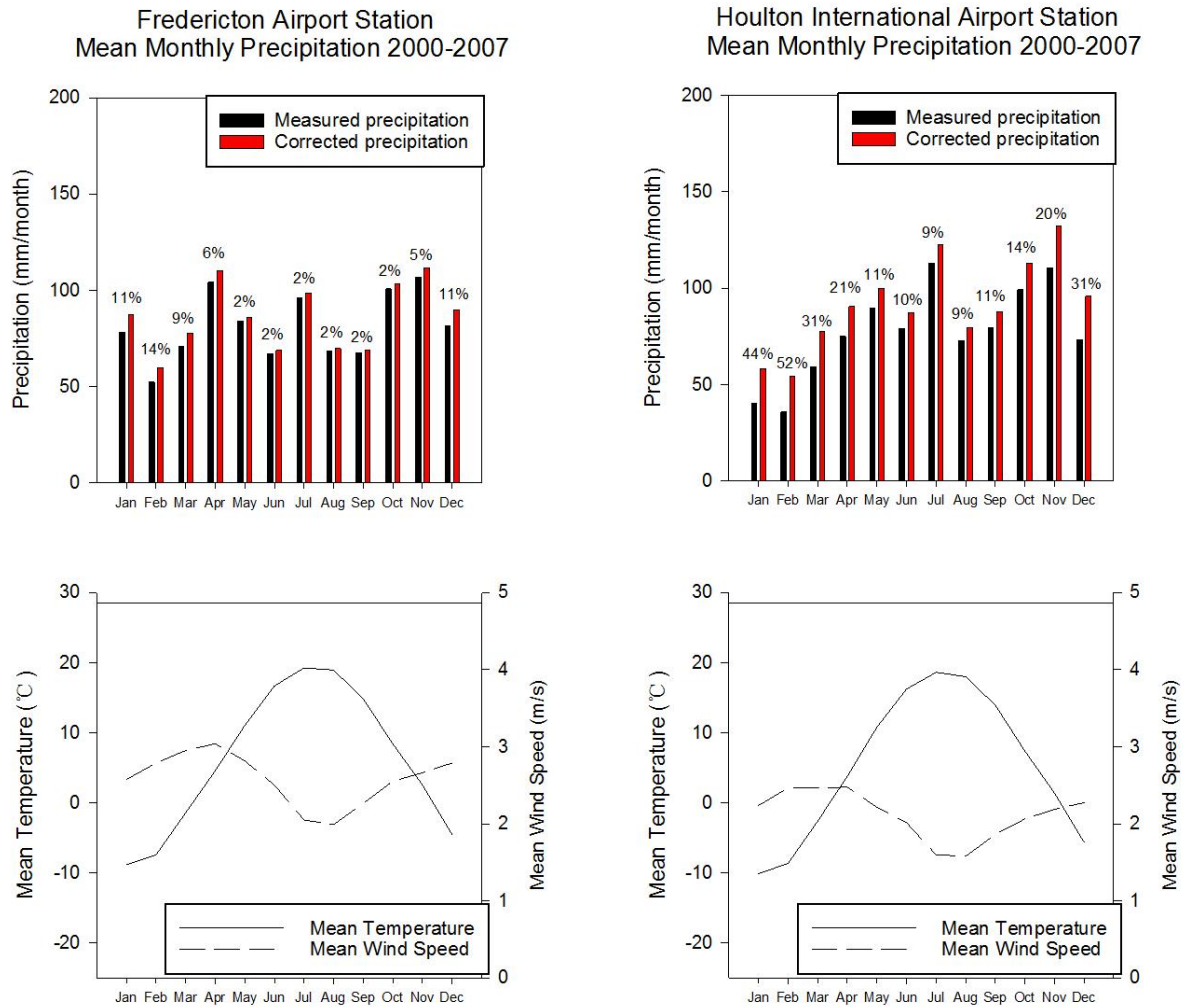


Figure 3-32. Mean monthly precipitation at Fredericton Airport station and Houlton International Airport station and corresponding mean monthly wind speed/air temperature (bottom panels) during 2000-2007. The percentage of each bar group represents the bias-correction change for that month.

Figure 3-34 and Figure 3-34 represent the monthly precipitation of each year in February and in July at Fredericton Airport station (Canada) and Houlton International Airport station (U.S.). Both figures show that the bias-corrections are lower at Fredericton Airport station than at Houlton International Airport station. Moreover, for both stations, the bias-corrections are higher in February than in July, which mainly due to the high wind speed in the cold months. Besides, the measured precipitation in both February and July is higher at Fredericton Airport station than at Houlton International Airport station for most years, especially for Houlton International Airport station. However, there is no obvious trend for precipitation in February or July over the eight years.

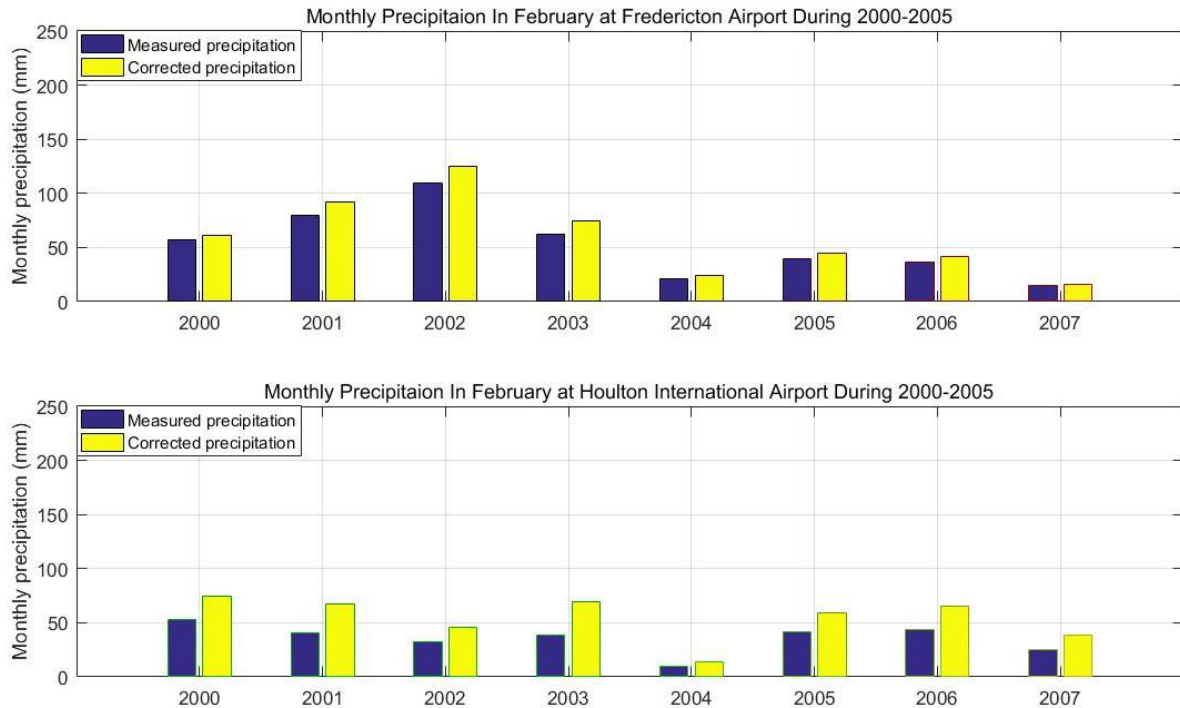


Figure 3-33. Monthly precipitation of each year in February at Fredericton Airport station (Canada, upper plot) and Houlton International Airport station (U.S., bottom plot).

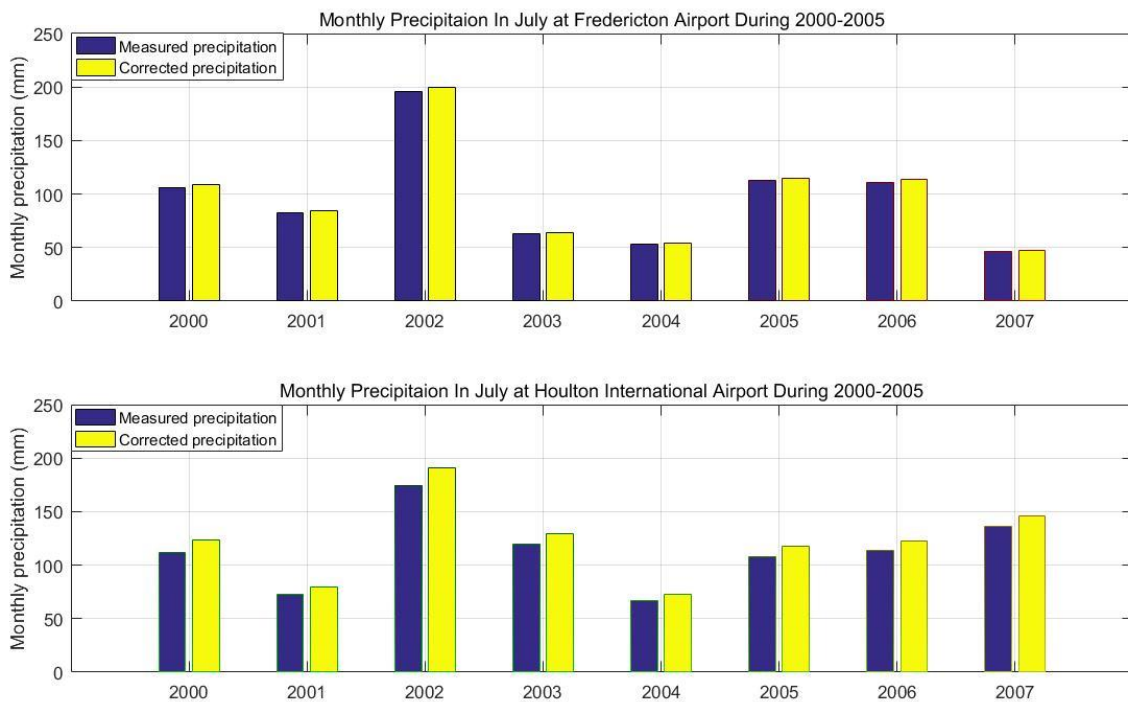


Figure 3-34. Monthly precipitation of each year in July at Fredericton Airport station (Canada, upper plot) and Houlton International Airport station (U.S., bottom plot).

### 3.6.3 Annual Precipitation

Figure 3-35 represents the annual measured and corrected precipitation for Fredericton Airport and Houlton International Airport during 2000-2007. The percentage of each bar group represents the bias-correction change for that year. The annual maximum precipitation (both measured and corrected precipitation) for both stations occurs in 2005. The annual minimum precipitation (both measured and corrected precipitation) for Houlton International Airport occurs in 2001, but for Fredericton Airport station, the annual minimum measured and corrected precipitation moved from 2001 (729 mm) to 2004 (771 mm). The results indicate the precipitation ranks at Fredericton Airport station changed due to bias-corrections. Also, Figure 3-35 shows that both measured and corrected precipitation is higher at Fredericton Airport station from 2001 to 2004; however, they are higher at Houlton International Airport station from 2005 to 2007. Also, Figure 3-35 displays that, from 2000 to 2007, the bias-corrections at Fredericton Airport station range from 5% to 7%, but the bias-corrections at Houlton International Airport station range from 15% to 21%, indicating that Houlton International Airport station has higher bias-corrections than Fredericton Airport station.

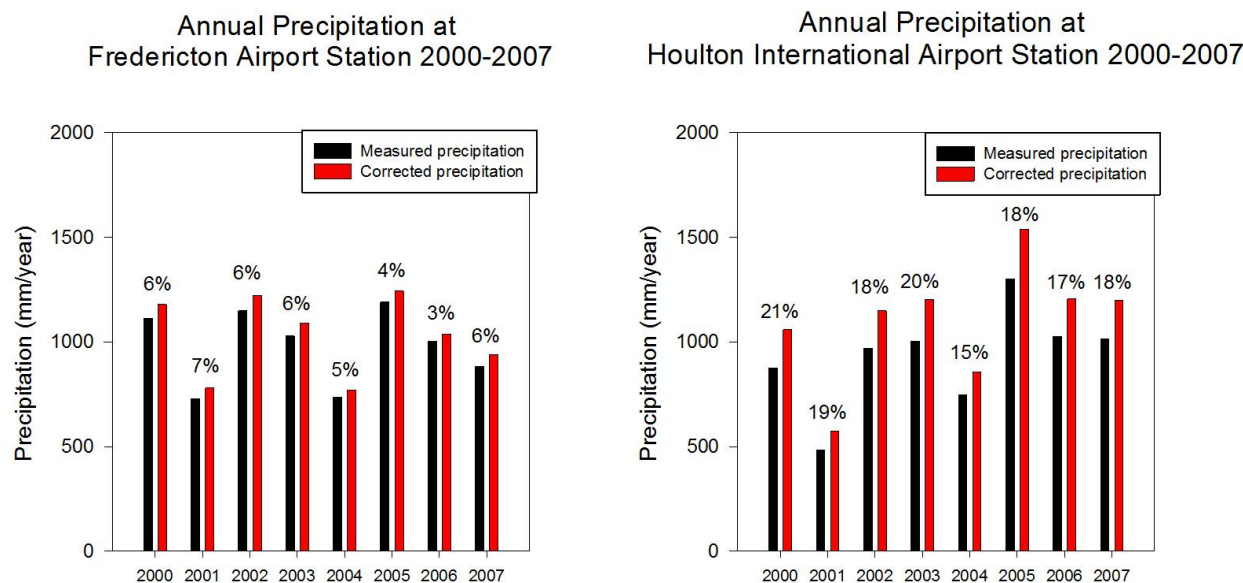


Figure 3-35. Annual measured and corrected precipitations for Fredericton Airport station and Houlton International Airport station during 2000-2007. The percentage of each bar group represents the bias-correction change for that year.

### 3.6.4 Seasonal Precipitation (Warm/Cold Seasons)

Figure 3-36 shows the mean annual measured and corrected precipitation for the cold and warm months at Fredericton Airport station and Houlton International Airport station. The percentages are the changes from measured precipitation to corrected precipitation relative to the amount of measured precipitation. This figure displays that the total measured precipitation for Fredericton Airport station and Houlton International Airport station is 979 mm and 927 mm, respectively; the total corrected precipitation for these two stations is 1032 mm and 1098 mm, respectively. These data show that Fredericton Airport station has higher measured precipitation, but after bias-corrections, Houlton International Airport station has higher corrected precipitation, which implies the gradient's direction change due to bias-corrections. The overall bias-corrections are 5.5% for Fredericton Airport station and 18.4% for Houlton International Airport station. Within these data, the changes in the warm months are 3.1% for Fredericton Airport station and 13.1% for Houlton International Airport station; the changes in the cold months are 11.2% for Fredericton Airport station and 36.9% for Houlton International Airport station. Overall, these results indicate that the Houlton International Airport station has higher corrections than Fredericton Airport station, especially for cold months. This change is mainly due to the low undercatch for snowfall measurements. Moreover, as these two stations are located 102 km apart, the precipitation difference between them may also due to the spatial distribution (Yang et al., 2003).



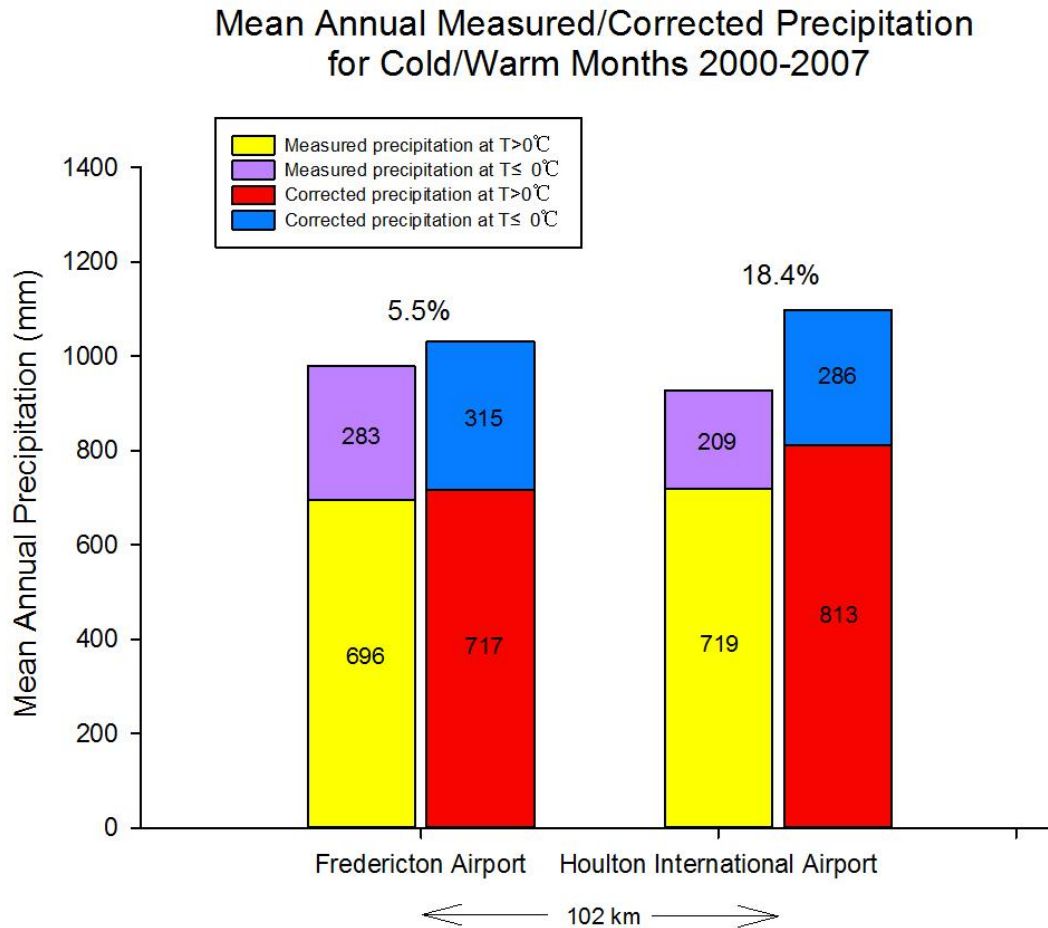


Figure 3-36. Mean annual measured and corrected precipitation for cold ( $\text{Temp} \leq 0^{\circ}\text{C}$ ) and warm ( $\text{Temp} > 0^{\circ}\text{C}$ ) months at Fredericton Airport station and Houlton International Airport station. The percentages represent the overall bias-corrections. The bottom number shows the distance between the two stations.

### 3.6.5 Monthly Precipitation Relationship

Figure 3-37 shows the scatter plots between Fredericton Airport station and Houlton International Airport station for the measured and corrected precipitation. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months. The left plot displays that the  $R^2$  for measured and corrected precipitation are 0.42 and 0.45, respectively. The right plot displays that the  $R^2$  for measured and corrected precipitation are 0.39 and 0.40, respectively. According to  $R^2$  values, the results suggest that the relationships between these two stations are weak in both warm and cold months; however, the relationships are stronger in the warm months than in the cold months for both measured and corrected precipitation. Also, according to the shifts of the



regression lines, the difference between measured and corrected precipitation are almost the same in the cold and warm months. The difference is mainly due to the high bias-correction at Houlton International Airport station.

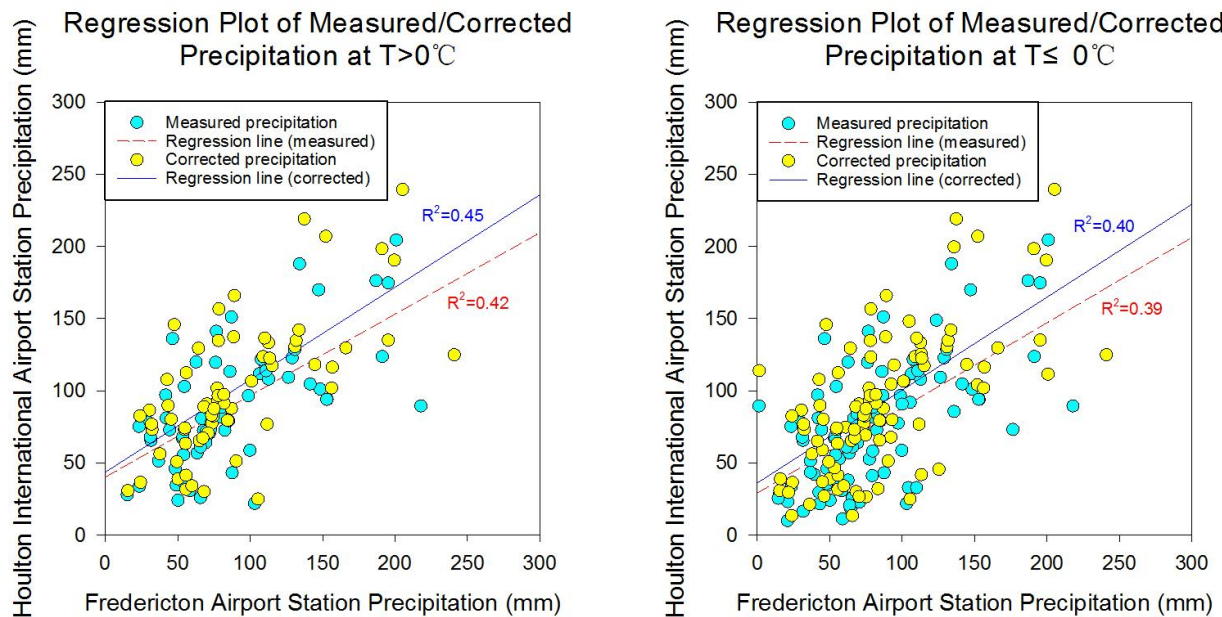


Figure 3-37. Scatter plots between Fredericton Airport station and Houlton International Airport station for the measured and corrected precipitation. The left plot represents the corresponding monthly precipitation in the warm months, and the right plot represents the corresponding monthly precipitation in the cold months.

### 3.6.6 Accumulation of Monthly Precipitation

Figure 3-38 represents the DMCs between Fredericton Airport station and Houlton International Airport station during 2000-2007. This plot indicates that the accumulated measured precipitation is higher at Fredericton Airport station, but the accumulated corrected precipitation is higher at Houlton International Airport station at the end point, which implies the gradient's direction changed due to bias-correction. Also, the slopes of both curves changed in the early years, indicating the relationships between the two stations are not constant over time. The inconstant slopes imply the existence of discontinuity in precipitation measurements across the border. At the end points, from the measured precipitation to corrected precipitation, the point shifts more upward than to the right side, which indicates the bias-corrections are higher at Houlton International Airport station than at Fredericton Airport station. Also, at the end points, the difference of measured precipitation between these two stations is about 412 mm; however, the

difference of corrected precipitation between these two stations increases to 512 mm. Therefore, it reveals that the observed (measured) precipitation difference underestimates the precipitation difference between the paired stations.

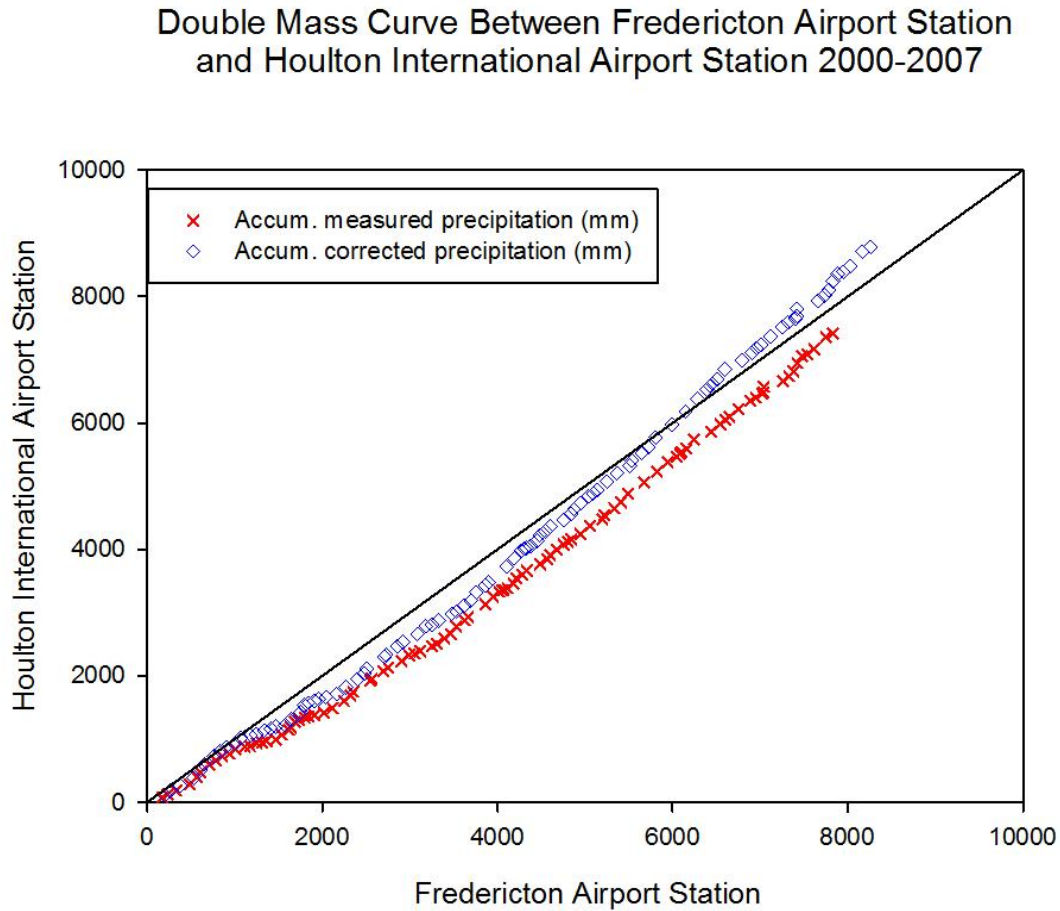


Figure 3-38. Double mass curve between Fredericton Airport station and Houlton International Airport station from 2000 – 2007.

## **Chapter 4. Comparison of Results Along the Border**

Chapter 3 displayed how Canadian and U.S. precipitation measurements distributed across the border. This chapter examines how monthly and seasonal precipitation distributed along the border; how the monthly precipitation relationship changed along the border, and how the accumulation of monthly precipitation changed along the border.

### **4.1 Monthly Precipitation**

According to Figure 4-1, Figure 4-2 and Figure 4-3, the results show that the monthly precipitation distributions for the paired stations are different, except pair 4. The different precipitation distributions may be due to elevation (pair 2, 3 and 6), or climate types (pair 2). For most station pairs (except the Canadian station in pair 1), the cold months are from November/December to February/March, and the warm months are from March/April to October/November. However, for the Canadian station in pair 1, its cold month is only January, and its warm months are from February to December. Besides, the peaks of monthly precipitation for all paired station did not occur in the same month, although in the same seasons (except for pair 1). For pair 2, 4 and 6, their peaks of monthly precipitation occurred in the warm months; while the peaks for pair 3 and 5 occurred in the cold months. However, the peak of monthly P for pair 1 occurred in the warm months at the Canadian station but in the cold months at the U.S. station. Moreover, there is only one paired station (pair 6) had the lowest precipitation in the same month, and three paired stations (pair 1, 3 and 6) had the lowest precipitation in the same month.

According to the bias-corrections for rain and snow, the bias-corrections are higher for snow (cold months) than for rain (warm months) at each station pair. Also, the bias-corrections for both rain and snow are higher at the U.S. stations than at the Canadian stations for all paired stations (except pair 3). For pair 3, the bias-corrections for both rain and snow are higher at the Canadian stations than at the U.S. stations, mainly due to the high wind speeds at U.S. station. Besides, except for pair 3, the average bias-corrections range from 4% to 12% for the Canadian stations,

and from 12% to 40 % for the U.S. stations. The results indicate that the average bias-corrections for each paired station are higher at the U.S. station than at the Canadian station (except for pair 3). The lower corrections for the Canadian stations are mainly due to the lower undercatch for the Nipher snow gauge as well as the lower wind speeds in the cold months. For pair 3, the average bias-corrections are 37% for the Canadian station, and only 21.9% for the U.S. station. The higher bias-correction at the Canadian station in pair 3 is mainly caused by the high wind speeds in the cold months.

The results also show that the mean temperature for the paired stations are very close: difference less than 1.8°C. Usually, the mean temperature is higher at U.S station, except pair 1 and 6. For wind speed, the results display that pair 2, 3 and 4 have higher mean wind speed (between 2.9m/s and 4.0m/s) than the other three station pairs. Their higher wind speeds are mainly seen in plain area. Therefore, the higher wind speeds at these three station pairs cause the higher overall bias-corrections than other station pairs: the bias-corrections range from 2 to 74% for the Canadian stations, and from 11 to 107% for the U.S. stations; however, for the other three pairs, the bias-corrections range from 2 to 19% for those Canadian stations, and from 2 to 52% for those U.S. stations. Moreover, the results also reveal that the overall bias-corrections are much higher at most U.S. stations than the Canadian stations.

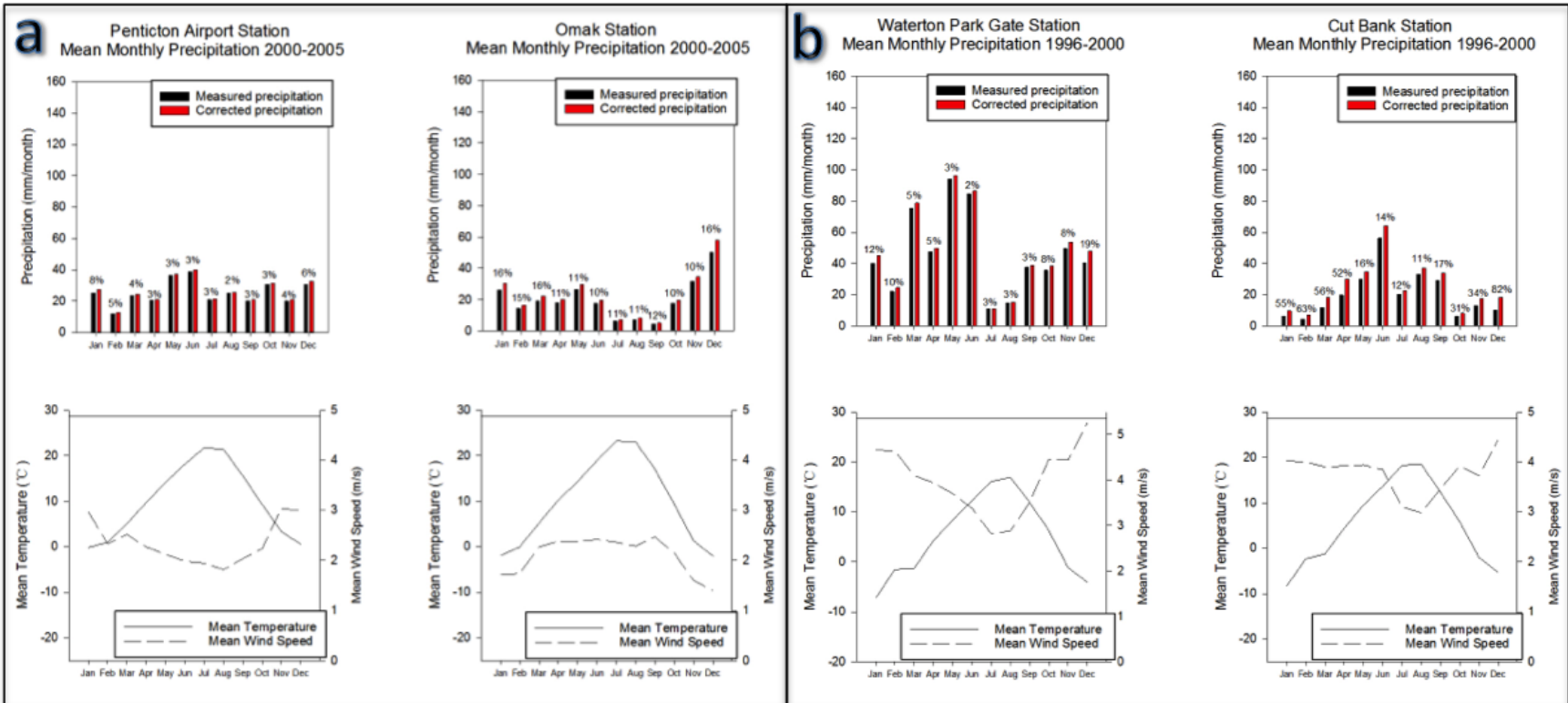


Figure 4-1. Mean monthly precipitation at (a) pairs 1 and (b) pair 2, and their corresponding mean monthly wind speed/air temperature. The percentage on each bar group represents the bias-correction change for that month.

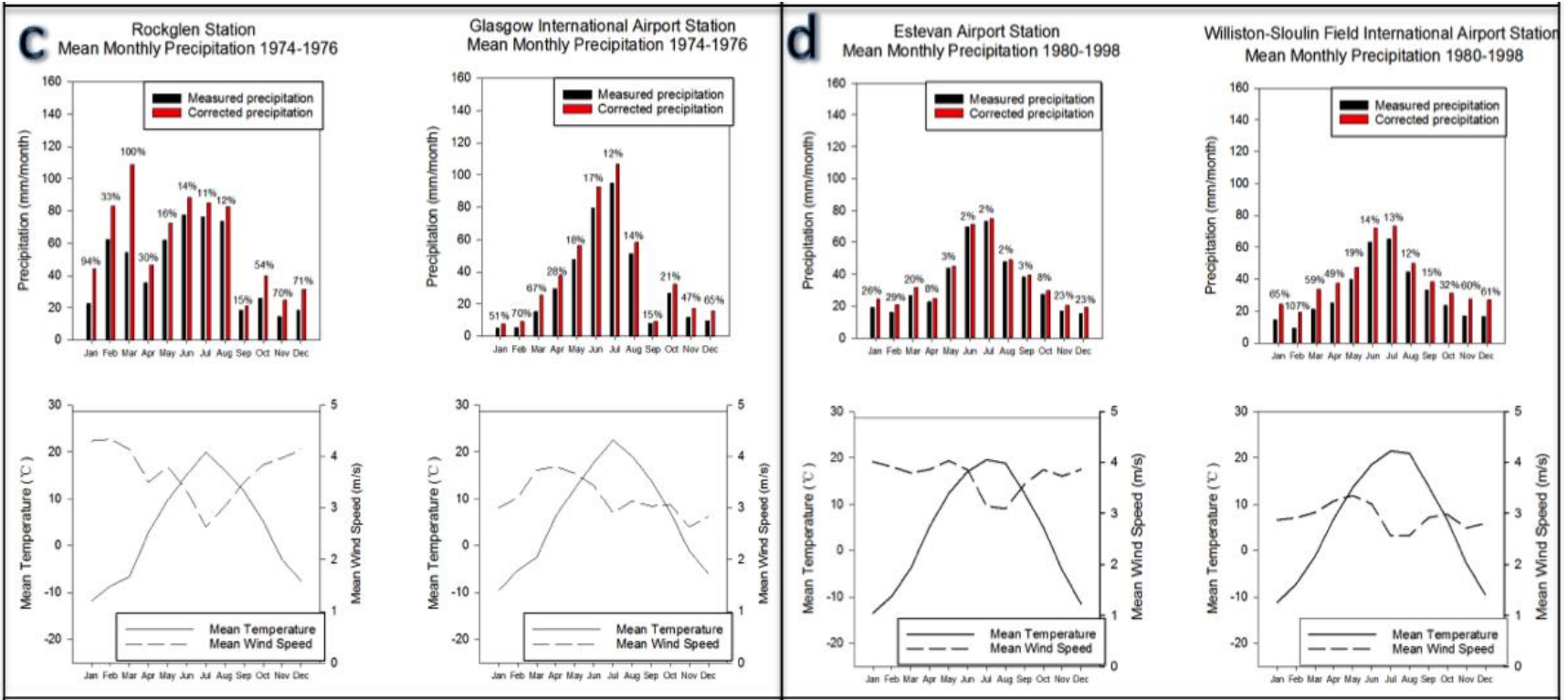


Figure 4-2. Mean monthly precipitation at (c) pairs 3 and (d) pair 4, and their corresponding mean monthly wind speed/air temperature. The percentage on each bar group represents the bias-correction change for that month.

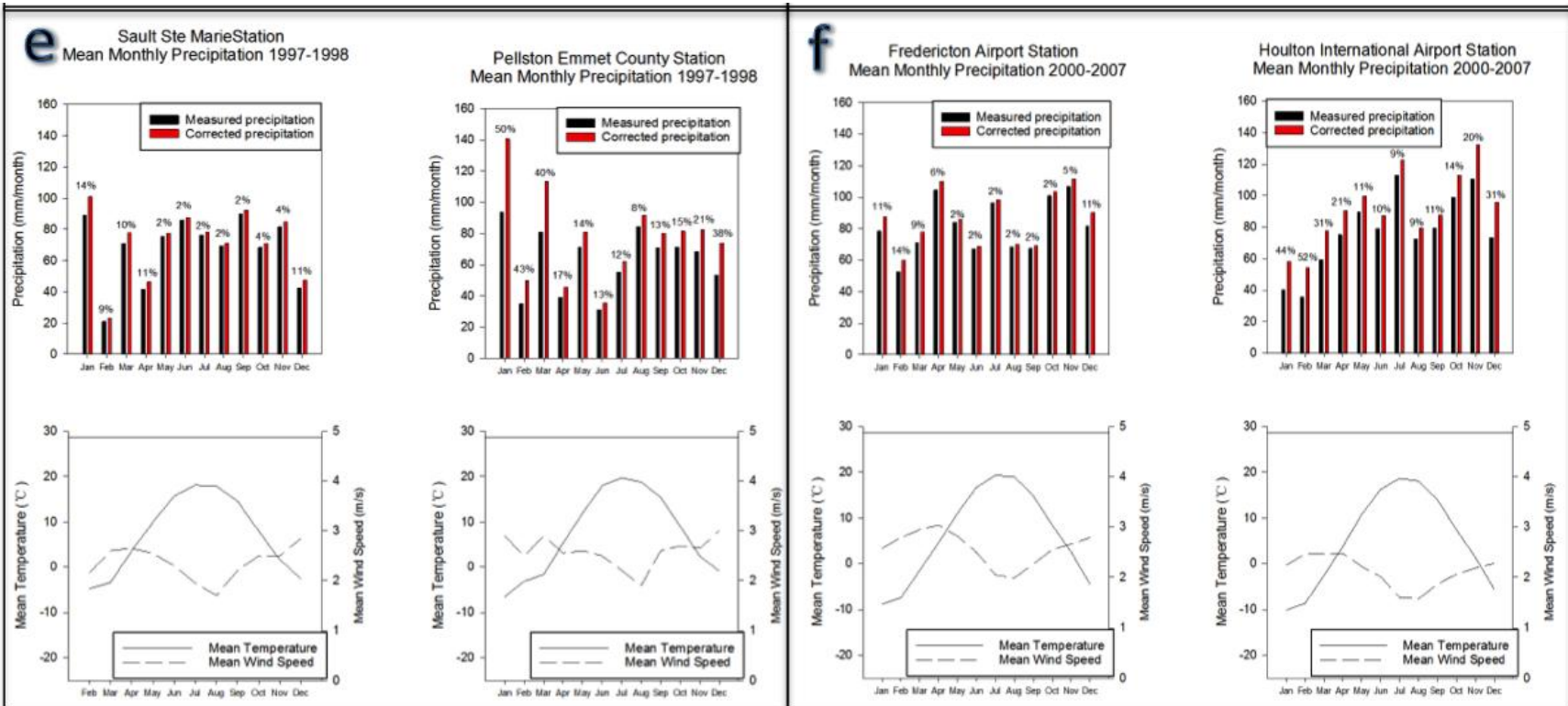


Figure 4-3. Mean monthly precipitation at (e) pairs 5 and (f) pair 6, and their corresponding mean monthly wind speed/air temperature. The percentage on each bar group represents the bias-correction change for that month.



## 4.2 Seasonal Precipitation (Warm/Cold Seasons)

Figure 4-4 represents the summary of mean annual measured and corrected precipitation for the warm and cold months for six paired stations. From (a) to (f), the plots represent the station pairs from west to east along the border. Figure 4-4 indicates that all stations have more rainfall than snowfall for both measured and corrected precipitation, except the corrected precipitation at Glasgow International Airport station (U.S.).

Figure 4-4 shows that all paired stations have higher bias-corrections at the U.S. station than the Canadian station, except for pair 3 (Rockglen and Glasgow International Airport stations). For pair 3, the bias-corrections are higher at the Canadian station mainly due to its high wind speed at cold months: the average wind speed at Rockglen station (CA) is 4.2 m/s, and the average wind speed at Glasgow International Airport station (U.S.) is only 3.1 m/s.

Figure 4-4 also implies that, for pair 4, 5 and 6, the measured precipitation is higher at the Canadian stations; however, after bias-corrections, the corrected precipitation is higher at the U.S. stations, which implies the gradient's direction changed due to bias-correction for these three station pairs. The result also reveals the significance of the bias-correction. At last, from west to east, the six paired stations can be divided into four groups, i.e. west coast group (pair 1), prairies group (pair 2, 3 and 4), central group (pair 5) and Atlantic group (pair 6). Figure 4-4 shows the precipitation distributions gradually increase from the western group to the eastern group. Besides, Figure 4-4 indicates that both measured and corrected precipitation at Waterton Park Gate station is higher than at Cut Bank station (311 mm and 284 mm differences for measured and corrected precipitation, respectively). It is mainly caused by their different climate types: Waterton Gate Park station has a humid continental climate, while Cut Bank station has a semi-arid climate, which has less precipitation than humid continental climate. Therefore, precipitation at Waterton Park Gate station is higher than at Cut Bank station.



### Mean Annual Measured/Corrected Precipitation for Cold/Warm Months

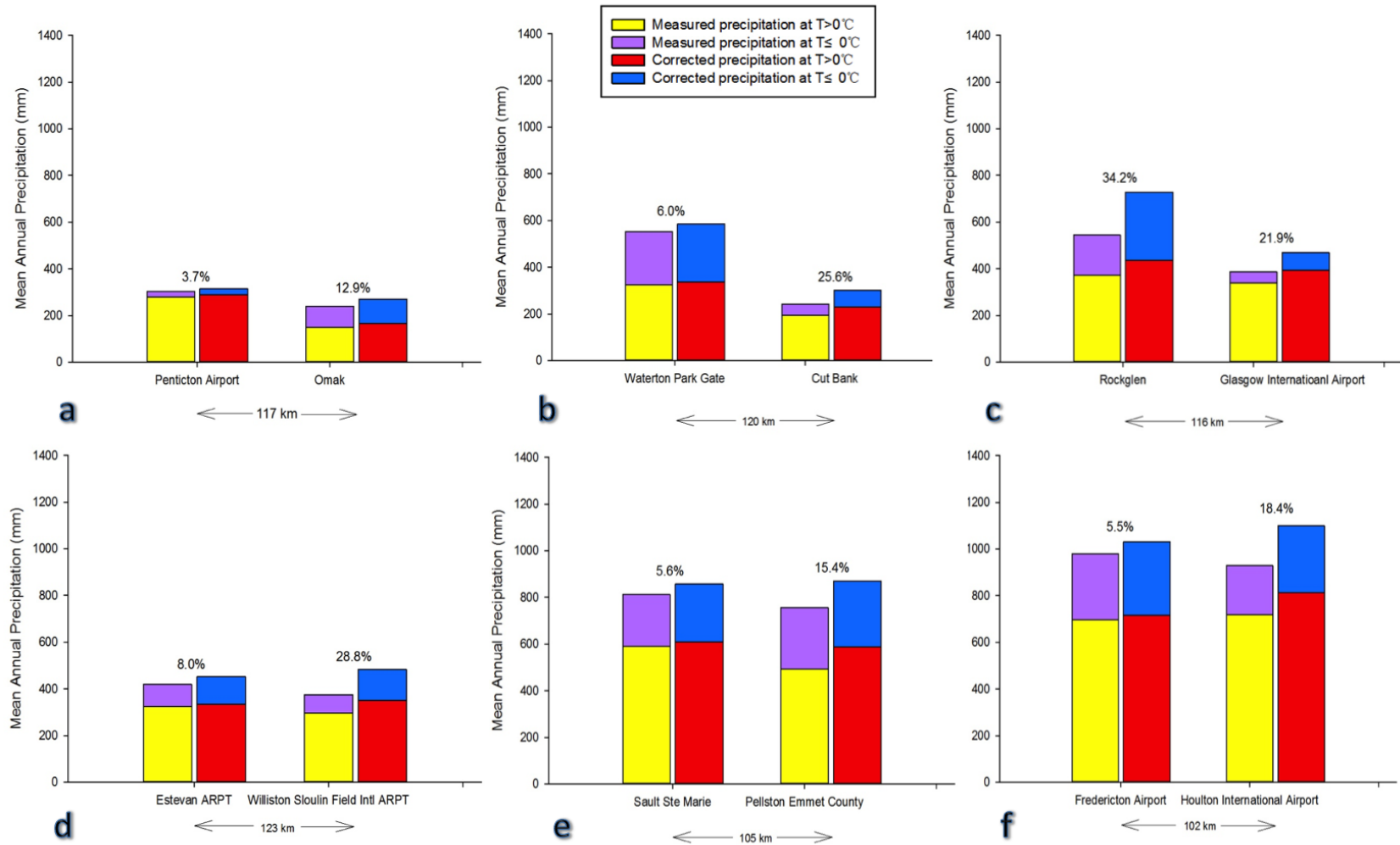


Figure 4-4. Summary of mean annual measured and corrected precipitation for warm ( $T > 0^{\circ}\text{C}$ ) and cold ( $T \leq 0^{\circ}\text{C}$ ) months for paired stations. From (a) to (f), the plots represent the station pairs from western to the eastern side along the border. The percentage represents the total bias-correction for each station.

Since the distances between each paired station are different, it is difficult to compare them with the various distances. Therefore, the gradients for each station pair are summarized in Table 4-1 by using  $\Delta P_m$  and  $\Delta P_c$  divided by the distance between the paired stations. The data calculated in this table is based on mean annual precipitation, and the negative numbers represent the precipitation that higher at U.S. station than at Canadian station.

Table 4-1 shows the gradients of each paired station for different conditions: yearly overall gradients, gradients in warm and cold seasons. The results show that the overall gradients are both high (over 1 mm/km) for pair 2 and 3. While the yearly overall gradients for other four pairs are less than 0.7 mm/km. For pair 1, its gradients are high in the warm months, 1.11 mm/km and 1.04 mm/km, respectively. For pair 2 and 3, their gradients are high in the cold months (over 1 mm/1km), which mainly caused by high wind speed as well as low catch efficiency of NWS 8-inch gauge in U.S. For pair 4, 5 and 6, their gradients are relatively low (less than 1 mm/1km) for overall, warm and cold seasons. Also, for pair 1, 4 and 5, their measured precipitation gradients are smaller than their corrected precipitation gradients, which indicate that the differences in measured precipitation between paired stations overestimate the true precipitation differences. For pair 2, 3 and 6, their measured precipitation gradients are greater than their corrected precipitation gradients, indicating that the differences in measured precipitation between paired stations underestimate the true precipitation differences.

Table 4-1. Summary of differences between measured and corrected precipitation over distance for each paired station, including the differences in different conditions: yearly total, in warm and cold seasons. The negative number represents the precipitation is higher at U.S. station than Canadian station for this pair. Calculation based on mean annual precipitation.

Pair No.	Station Name	Measured precipitation gradient: $\Delta P_m/\text{distance}$ (mm/km)			Corrected precipitation gradient: $\Delta P_c/\text{distance}$ (mm/km)		
		Overall	Warm	Cold	Overall	Warm	Cold
1	Penticton Airport	0.54	1.11	-0.56	0.38	1.04	-0.67
	Omak						
2	Waterton Park Gate	2.60	1.08	1.51	2.36	0.88	1.48
	Cut Bank						
3	Rockglen	1.37	0.28	1.08	2.24	0.37	1.87
	Glasgow International Airport						
4	Estevan Airport	0.36	0.24	0.12	-0.24	-0.12	-0.12
	Williston-Sloulin International Airport						
5	Sault Ste Marie	0.55	0.93	-0.38	-0.13	0.19	-0.32
	Pellston Emmet County						
6	Fredericton Airport	0.50	-0.23	0.73	-0.65	-0.94	0.29
	Houlton International Airport						

### 4.3 Monthly Precipitation Relationship

Figure 4-5 represents the summary of regression plots for paired stations when the temperature is greater than 0°C, and Figure 4-6 represents the summary of regression plots for paired stations when the temperature is smaller or equal to 0°C. For each figure, from upper left to bottom right, the plots represent the six station pairs from west to east along the border.

As the magnitude of  $R^2$  value reflects the relationship between paired station, Figure 4-5 and Figure 4-6 indicate that, except for the cold months of pair 5, all the other pairs show that the  $R^2$  values are equal or less than 0.50, which indicates the relationships between the paired stations are weak in both warm months and cold months (both measured and corrected precipitation) for these station pairs; however, for the cold months of pair 5, the  $R^2$  for measured and corrected precipitation are 0.56 and 0.61, which indicate the relationships between this paired station are strong in the cold months. Moreover, as the shift of regression lines reflects the difference between measured and corrected precipitation, the results (Figure 4-5 and Figure 4-6) indicate that: in the warm months, the shifting of the regression lines (i.e. pair 1, 2, 3, 4 and 6) are small for all station pairs, which indicate the small differences between measured and corrected precipitation for all station pairs in the warm months. However, the shifting of the regression lines (i.e. pair 1, 4, 5 and 6) are great for pair 4 and 5 in the cold months, which indicate the large differences between measured and corrected precipitation for these two station pairs in the cold months. Moreover, if comparing the corresponding plots (warm months and cold months) for the same station pair (i.e. pair 1, 4 and 6), the results show smaller shift in the cold months for pair 1, indicating smaller difference between measured and corrected precipitation for this pair. The shift, on the other hand, is greater in the cold months for pair 4, which indicates greater difference between measured and corrected precipitation for this pair. The shifting is about the same in both warm and cold months for pair 6, this indicates the similar differences between measured and corrected precipitation for this pair.



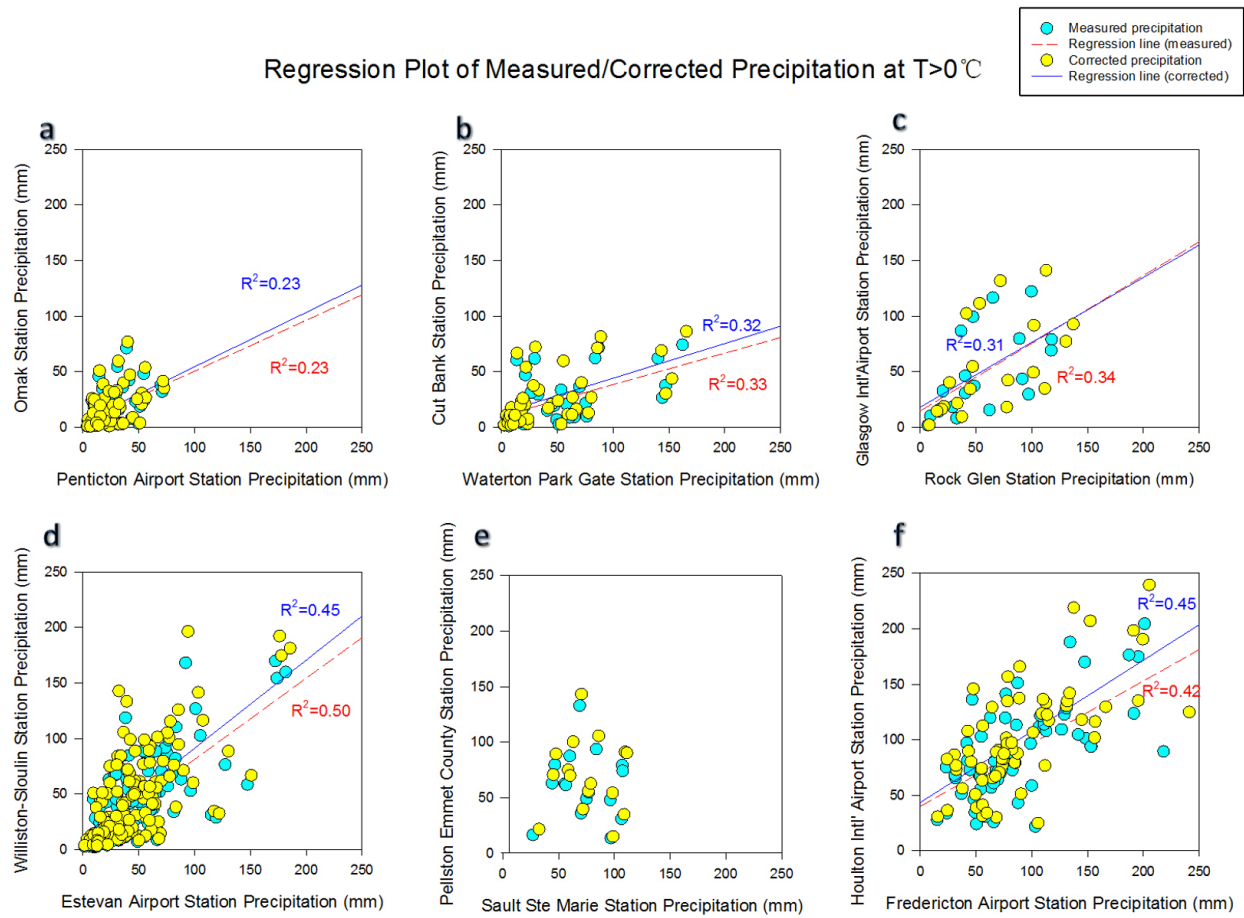


Figure 4-5. Summary of regression plots for paired stations when the temperature is greater than  $0^{\circ}\text{C}$ . From (a) to (f), the plots represent the station pairs from west to east along the border.

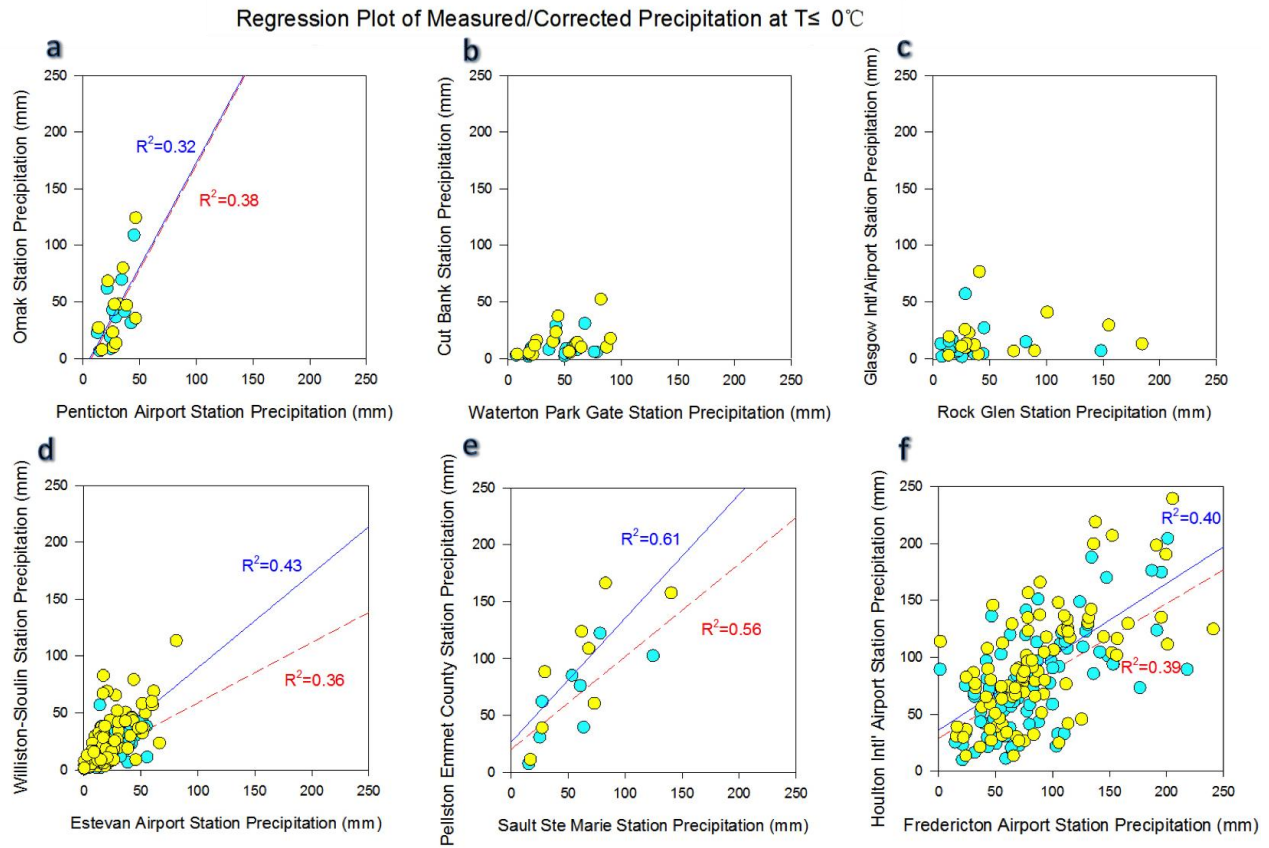


Figure 4-6. Summary of regression plots for paired stations when the temperature is smaller or equal to  $0^{\circ}\text{C}$ . From (a) to (f), the plots represent the station pairs from west to east along the border.

#### 4.4 Accumulation of Monthly Precipitation

Figure 4-7 represents the summary of DMCs for the paired stations. From top left to the bottom right, the plots represent the station pairs from west to east along the border. First of all, Figure 4-7 indicates that for pair 1, 2 and 3, both measured and corrected precipitation is higher at the Canadian stations than at the U.S. stations. However, for pair 4, 5 and 6, the measured precipitation is higher at the Canadian stations than at the U.S. stations at first; after bias-corrections, the corrected precipitation becomes higher at the U.S. stations, which implies the gradients' direction changed due to bias-corrections for these three stations.

Secondly, at the end points, the movements from the measured precipitation to corrected precipitation reflect the impact of bias-correction amounts for the paired stations. Figure 4-7 shows that except pair 3, the end points for all paired stations shift more upward than to the right side, which indicates the bias-corrections are higher at the U.S. stations than at the Canadian stations. For pair 3, the end points shifts more to the right side than upward, indicating the bias-corrections are higher at the Canadian stations than at the U.S. stations. It is mainly due to the higher wind speed at the Canadian station (4.2 m/s) than the U.S. station (3.1 m/s) in winter.

Moreover, at the end points, if comparing the difference of measured and corrected precipitation between the paired stations, the results show that, the differences are higher in measured precipitation than for the corrected precipitation for pair 1, 2 and 4; this results that the observed precipitation difference overestimates the true precipitation difference for these three station pairs; however, for pair 3, 5 and 6, the differences are higher in corrected precipitation than for measured precipitation, which implies that the observed precipitation difference underestimates the true precipitation difference for these three stations pairs. The last, but not least, as the slopes of the curves keep changing over time for all station pairs (except pair 4), which reveals the existence of discontinuity in precipitation measurements across the border.

# Double Mass Curve Between Canadian Stations and U.S. Stations

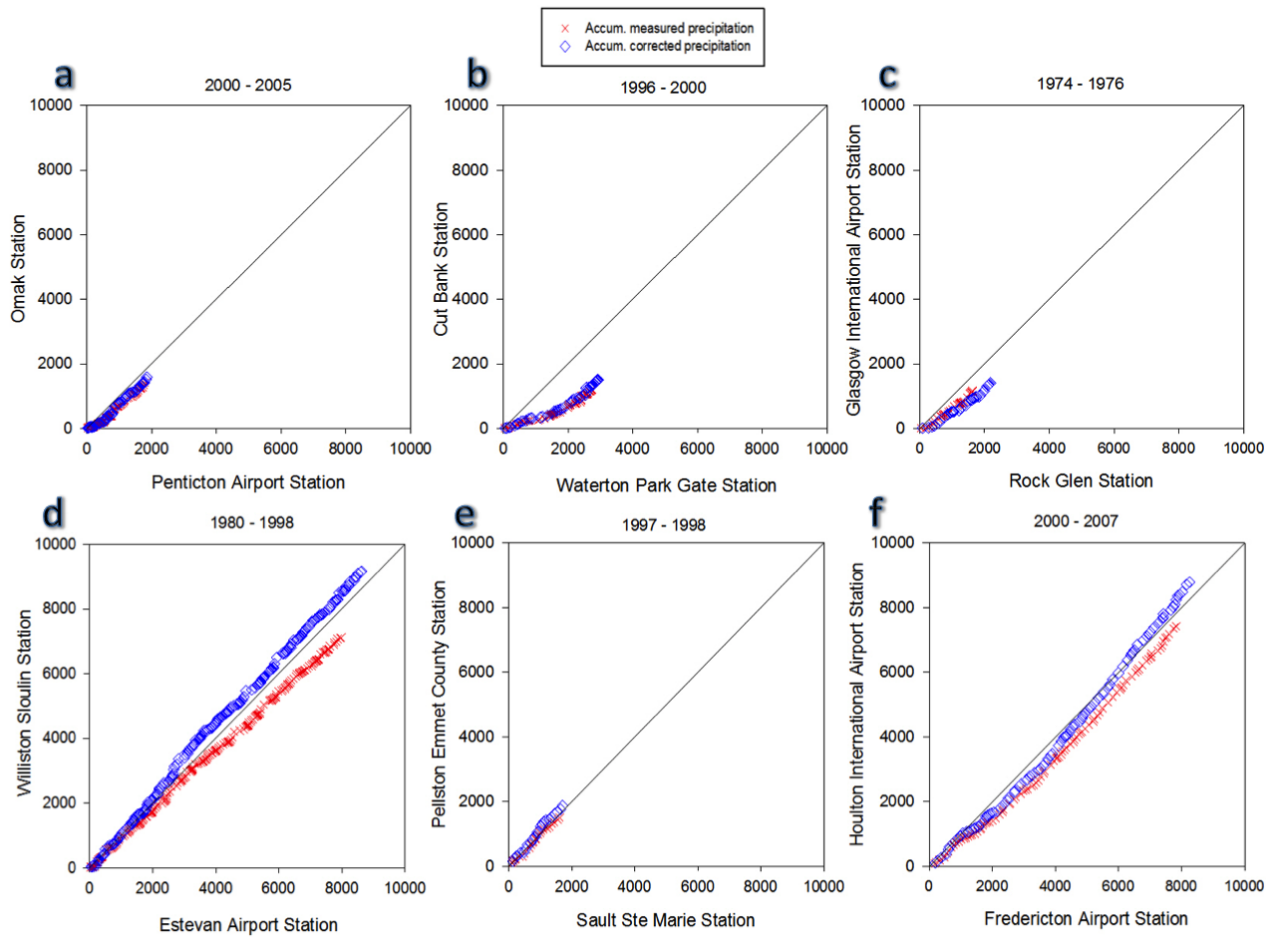


Figure 4-7. Summary of double mass curve for different paired stations. From (a) to (f), the plots represent the station pairs from the western to the eastern side along the border.



## **Chapter 5. Discussion**

The results and the comparison along the border have been discussed in Chapter 3 and 4. This Chapter 5.1 will compare the results of this study with other similar work. The most recent similar study was done by Scaff et al. (2015). Her work determined the inconsistency in P measurements across Alaska and Yukon border. The limitations of this study will be discussed in Chapter 5.2.

### **5.1 Comparison with Similar Work**

According to Scaff et al. (2015), the higher bias-corrections occurred in the northern region of Alaska and Yukon due to their lower temperature and higher wind speed. In this study, since the latitudes of each station pairs are closed, their mean temperatures are similar, which did not affect the bias-corrections significantly. Therefore, the monthly precipitation distributions display that the higher bias-corrections occurred in prairie's group due to the higher wind speed, which conforms with the results from Scaff et al. (2015). Moreover, in this study, the bias-corrections for snow are higher than for rain, which confirms the results from Scaff et al. (2015). Also, Scaff et al. (2015) stated that the corrections for both groups at the U.S. stations were higher than that at the Canadian stations. In this study, the bias-corrections for all pairs of U.S. stations are higher than those at the Canadian stations, except for pair 3. For seasonal precipitation, Scaff et al. (2015) indicated that, for the northern group, the measured precipitation showed an increasing pattern from west to east, but the corrected data showed a different pattern. However, in this study, the results are different. Also, in this study, only pair 4, 5 and 6 indicate the changes of gradient direction due to bias-correction; but in Scaff et al. (2015), the gradient direction changed in both groups. According to Scaff et al. (2015), the correlations are higher in the cold months than in the warm months for both groups, and only the northern group showed a shift in regression line in cold season. In this study, except for the cold months of pair 5, all other station pairs show the weak relationships for both warm and cold seasons. Also, the cold months of pair 4, 5 and 6 display the great shifting in regression lines, which means the large difference between measured and corrected precipitation for these station pairs in cold months. At last, the DMCs from Scaff et

al. (2015) revealed that both groups in her study show the shifting in the DMCs, which indicates the

gradient's direction changed across the border; also, her results showed that the measured precipitation of both groups overestimate precipitation gradient without bias-corrections. In this study, only pair 4, 5 and 6 indicate the gradient's direction changed across the border. Also, pair 1, 2 and 4 show that the differences in measured precipitation overestimate precipitation gradient without bias-corrections, and pair 3, 5 and 6 show that the differences in measured precipitation underestimate precipitation gradient without bias-corrections. At last, in both studies, all results (except pair 4) show the existence of discontinuity in precipitation measurements across this national border.

## **5.2 Limitations**

The main limitation of this research is to find common periods among stations, which is mainly due to data quality and data availability.

Based on the selection criteria, among the dataset, more than six pairs of stations can be selected; however, the results showed that many stations had been confirmed not to have/use the historical national standard manual gauges during a specific period, or their information could not be confirmed. Therefore, many potential stations were eliminated during the first step even they have better data quality. Also, there are more stations across the border with shorter distance but cannot be chosen, due to no consecutive monthly data over one year. Therefore, the stations with longer distance need to be selected to replace them, which may bring some uncertainty to this study.

According to the data quality, some observed monthly precipitation data are recorded zero. If ascending to its daily precipitation data, the results show that the daily precipitation data for that month are all zero, which may represent missing observations. The missing data are eliminated in this study, which may affect the results for lower and trace precipitation. Besides, as some station

pairs only have very short records, such as two-year records, their regression plots and their DMCs show weak relationships between paired stations.

Also, according to the selected station pairs in this study, most of them do not have common data period or years. This may bring uncertainties when comparing the data of station pairs along the border. Furthermore, based on the site map (Figure 2-1), the western half of the borderline was covered by four pairs of stations; however, the eastern half was only covered by two pair of stations, which is insufficient to represent the eastern part. Therefore, more station pairs need to be included in the future to increase the accuracy of the analysis.

## Chapter 6. Conclusion

This study quantified changes in precipitation amount due to the bias-corrections at Canada/U.S. border stations, examined precipitation distribution and its change due to bias-corrections across and along the border, and also determined the discontinuity in precipitation measurements across the border.

Firstly, the statistical analyses show that the bias-corrections for all the U.S. stations have higher bias-corrections compared to the Canadian stations (except one station pair), especially for cold months. For the excepted pair, the higher bias-corrections at the Canadian station are mainly due to the high wind speed in the cold months. Also, half of the station pairs show that the gradient's direction changed after bias-corrections, which indicates the significance of the bias-correction, especially for the U.S. gauge in the cold months. Moreover, along the border, the stations are divided into four groups: west coast group, prairies group, central group and Atlantic group. The seasonal precipitation plots reveal that the precipitation increases from the west to the east groups along the border. Secondly, the regression analysis implies that the relationships between paired stations are weak in both warm and cold seasons for most station pairs. Also, this analysis indicates that the differences between measured and corrected precipitation are small in the warm months for most station pairs. Thirdly, the DMCs show that the end points shift (from measured to corrected precipitation) more upward than to the right side, which implies that the bias-corrections are higher at the U.S. stations than at the Canadian stations for most station pairs. Moreover, if comparing the difference between measured and corrected precipitation of paired stations, half of the station pair shows that their observed precipitation differences underestimate the true precipitation gradients, and the other half shows that their observed precipitation differences overestimate the true precipitation gradients. Besides, both statistical analysis and DMCs display that, after bias-corrections, the higher precipitation changed from Canadian stations to the U.S. stations for half of station pairs, which reveal that the gradients' direction changed due to bias-corrections. Moreover, the slope changes of the DMC curves revealed the significant discontinuity in the precipitation measurements across the Canada and U.S. border.

This study is very important because it directly contributes to the regional climate and hydrology research and applications. Also, this work may influence the basin and regional water balance calculation significantly. Moreover, the results from this work can affect the accuracy of wet deposition calculation. Furthermore, more work should be done in the future, such as more station pairs need to be selected to improve the reliability of the results across and along the border, and longer data period should be chosen to enhance the results of similar studies.

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